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DEPOSITIONAL ENVIRONMENT OF FINE-GRAINED SEDIMENTS IN LATE-GLACIAL LAKE PENTICTON

by

© MICHAEL JOHN KENT

A THESIS

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ABSTRACT

The aim of this thesis is to interpret the depositional environment of the fine-grained glaciolacustrine sediments in the Okanagan Valley, British Columbia. The extensive "white" silt terraces bordering Okanagan Lake illustrate rapid deposition in proglacial Lake Penticton. Seven sections were logged, three on the east, and four on the west side of Okanagan Lake. Internal grain size and structural properties are assigned to five facies states and describe the sedimentary successions. Transition probabilities, grain size, paleocurrent and varve correlation analysis are used to interpret the sedimentary environment and depositional processes.

Lower sediments are coarse grained and two successions are recognised: (i) flat-bedded, inclined and structureless sands alternate with coarse laminated silt; (ii) flat-bedded sands alternate with crosslaminated sands. These cyclic sedimentary successions are interpreted as channel deposits and distributary mouth bar deposits laid down by density currents in glaciolacustrine deltas.

A transition environment is proposed overlying the coarse-grained deposits. Rapid alternating beds of flaser, ripple formsets, type B ripple drift, contorted bedding occur within both sand and silt size sediment and indicate

ABSTRACT

The aim of this thesis is to interpret the depositional environment of the Pleistocene glaciolacustrine sediments in the Okanagan Valley, British Columbia. The so-called "white" silt deposits typically [illegible] [illegible] rapid deposition in glacial lake Penticton. Seven sections were logged, three on the east, and four on the west side of Okanagan Lake. Sediment grain size and structural properties are applied to five facies groups and describe the sedimentary environment. Statistical probabilities, grain size, paleocurrent and other correlation methods are used to interpret the sedimentary environment and depositional processes.

These sediments are mainly graded with [illegible] properties are recognized: (1) flat-bedded, laterally extensive sand units alternate with graded laminated silt; (2) flat-bedded sands alternate with [illegible]. These facies sedimentary associations are interpreted as channel deposits and distributary [illegible] down by density currents in glaciolacustrine [illegible].

A transition environment is proposed containing the coarse-grained deposits. Rapid alternating sets of climbing ripple laminae, type B ripple drift, [illegible] occur within both sand and silt size sediment and indicate

more distal deposition in sub-aqueous levees.

The third environment is characterized by thick lower silt and clay varved deposits fining vertically, and reflects deposition in a glaciolacustrine environment. Grain size analysis indicates that the silt units were deposited by a series of underflow events responding to meltwater discharge. Upper varved clay units contain sand stringers and are believed to indicate winter underflow events.

Evidence from this study suggests that lateral streams built up tributary deltas into a developing proglacial lake covering an ice mass mantled with sediment in the center of the valley. Sedimentation was rapid and varve counts indicate that lacustrine sedimentation occurred for approximately 80 years.

ACKNOWLEDGEMENTS

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This thesis would never have seen the light-of-day if it was not for the motivating force of Sandra. I am truly thankful.

Finally, I wish to dedicate this thesis to my father who died just before it was completed. He would have been pleased to see its completion.

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CHAPTER I

INTRODUCTION

1.1 Background to the Study

In mountain valleys during retreat stages of the Pleistocene ice-bodies, long narrow ice-dammed lakes are often formed in temporary basins. Flint (1971, p. 192) suggests these ice-marginal lakes occurred where, ... "the margin of a glacier advanced over ice-free ground that sloped down toward the glacier." Although these lakes were ephemeral, often thick deposits of sand, silt and clay were deposited in them by meltwater issuing from the ice-front, and by streams from adjacent areas. Embleton and King (1971) cite strandlines, terracettes, deltas, and lake plains overlying bottom deposits of laminated silt and clays as distinctive landforms developed in these glacio-lacustrine sediments. Of these landforms, deltas are some of the most interesting from a geomorphological point of view as they contain within their structures a detailed history of the events responsible for their formation.

Pleistocene glacio-lacustrine deltas consist of coarse-grained deposits (mainly sand) generally deposited proximal to the ice-front under high rates of meltwater discharge. Flint (1971) states that a small delta can accumulate very quickly, perhaps in a single season.

With ice-front retreat and an increase in size of the lake, fine-grained sediments are deposited on the lake floor beyond, or on top of the coarser deltaic deposits. Lake floor deposits beyond the limit of delta growth are predominantly fine, and become increasingly so as the distal parts of the lake are approached (Embleton and King, 1971). These deposits frequently exhibit rhythmical laminations, or couplets, revealed in changes in grain-size. They result from variations in the supply of sediment and discharge variations in the depositing meltwater streams. Normally the lowest part of each couplet consists of coarse silt or fine sand, and the upper part is composed of clay. De Geer (1912) considered that in glacio-lacustrine rhythmites the coarse laminae were deposited in summer and the fine laminae in winter. He proposed that the term "varve", rather than rhythmite be used to denote a couplet of annual deposition.

Interpretation of varved sediments in northern Europe and eastern North America has been used as a geochronological tool for dating ice-retreat (De Geer, 1912; Antevs, 1925). However, these Pleistocene varved sediments also exhibit structures and texture changes that are related to the depositional process active at the time of sediment accumulation.

The determination of sedimentary processes is based on a comparison of ancient deposits with those of modern ones where the processes responsible for the observed properties are recorded (Shaw, 1975). Criteria used to elucidate processes are, sedimentary structures, directional properties, and grain-size. These can be used to make environmental interpretations regarding conditions at the time of deposition (see Chapter I, Section 1.5, and Chapter III).

Great thicknesses (20 - 50 m approximately) of exposed glacio-lacustrine sediments, evidence of deposition in former late-glacial lakes in the Interior Valleys of British Columbia, have been studied by a number of researchers (Flint, 1935; Meyer and Yenne, 1940; Nasmith, 1962; Fulton, 1965, 1969, 1975; Shaw, 1975). Flint (1935) discussed in qualitative terms the origin of the silt terraces bordering Lake Okanagan (fig. 1-1). He outlined a glacial sequence in which a down-wasting tongue of ice blocked the north-south drainage, creating temporary pro-glacial lakes. Streams from the ice-free upland areas, entering these lakes, deposited coarse material on proximal submerged stagnant ice blocks, and fines on the rock slopes between the streams. Meyer and Yenne (1940) conducted a study on the mineral assemblage of the 'white' silts. Mechanical analysis shows that the silt was derived locally as

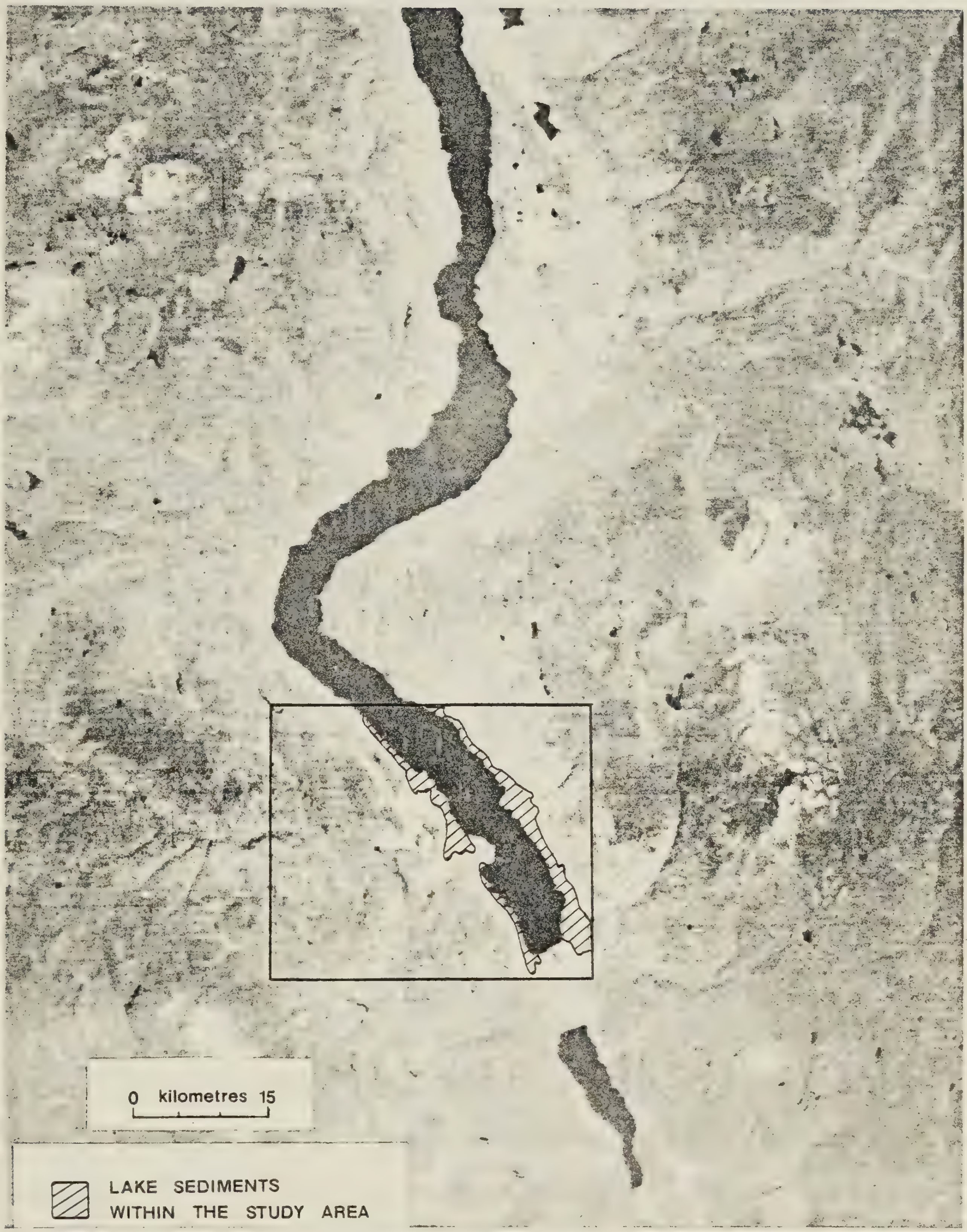


Figure 1-1 ERTS imagery highlighting the distribution of the 'white silts' alongside Okanagan Lake within the study area.

rock-four (composed principally of quartz and feldspar), while the angularity of the grains indicated a minimum of stream transport. They supported Flint's (1935, p.8) conclusions that, ... "the sediments represent accumulations of rock-flour at or near mouths of streams emptying into ice-dammed lakes ..." Nasmith (1962) described and mapped the late-glacial surficial deposits of the Okanagan Valley, but presented little information on, or interpretation of, the depositional environment of the silt terraces. He suggests that the glacial lake silts, which are so prominent a feature of this part of the Okanagan Valley, were deposited in Glacial Lake Penticton, and that the maximum elevation of the silts in the vicinity of Penticton was approximately 45 m above the present level of Okanagan Lake.

Fulton (1965) undertook a detailed study of the depositional environment of the silt in the South Thompson Valley. He suggested silt was transported by tributary streams from the ice-free uplands into glacial Lake Thompson. Utilizing Antev's (1925) technique for varve chronology, Fulton correlated varves over a distance of 5 km. While this analysis was not the major thrust of the study, Fulton states (1965, p. 566), "... a complete history of the sedimentation of the South Thompson silt could be written if the entire deposit could have been studied in this manner." In terms of stratification, Fulton considered the silt to be varved, with thick varves

grading upward to thin. However, he presents no detailed discussion on the depositional processes which produced the varved bedding.

A detailed discussion on the coarse-grained sediments deposited on glacio-lacustrine deltas of Edmonton and Okanagan Valley Pleistocene ice-marginal lakes is presented by Shaw (1975). He examined coarse proximal deposits in the Okanagan that underlie or grade laterally into fine lacustrine sediments. Shaw states (p. 285), "... the fine members of the lacustrine deposits are clearly varved and are believed to have been deposited in glacial lakes." The coarse members associated with the varved silts and clays are believed to have been deposited in deltaic bodies. Although these deposits are easily recognizable, Shaw suggests that the processes and conditions which produce distinctive varved bedding are still not clearly understood.

1.2 Objective

The principal objective of the study is to determine the depositional processes resulting in the fine-grained glacio-lacustrine sediments of Glacial Lake Penticton. These processes, and the environmental conditions in which they operated, may be determined by analysis of the vertical and lateral properties of the sediments. The methods of analysis are discussed in Chapter III.

1.3 General Site Selection

The fine-grained sediments of the southern Okanagan Valley were chosen for analysis of sedimentary associations for the following reasons:

1. With the exception of the study of silt deposition in the South Thompson Valley, no detailed environmental reconstruction based on the fine-grained sediments in the Okanagan has been undertaken.

2. The post-glacial climate has been sufficiently arid to preserve the glacial-lake sediments and thus favor the interpretation of a relatively complete record of deposition.

3. Terraces of glacial-lake sediments are found along the shore of Okanagan Lake and provide good exposures for measurement and attempted reconstruction of the depositional environment.

1.4 Site Description

The Okanagan Valley is a broad north-south trending steep-walled trench cutting through the Interior Plateau of British Columbia and the Columbia Plateau of north-central Washington (Nasmith, 1962). In British Columbia, the valley extends from latitude $49^{\circ}00'$ north to 50° 43' north and is generally aligned along longitude 119° 30' west (fig. 1-2). The trench is occupied by the Okanagan Lake (elevation 342.2 m, 1956 datum) and the Okanagan River. The width of the valley bottom ranges from about one to six kilometres with elevations ranging from 270 m near Osoyoos to 550 m west of Enderby (Nasmith, 1962).

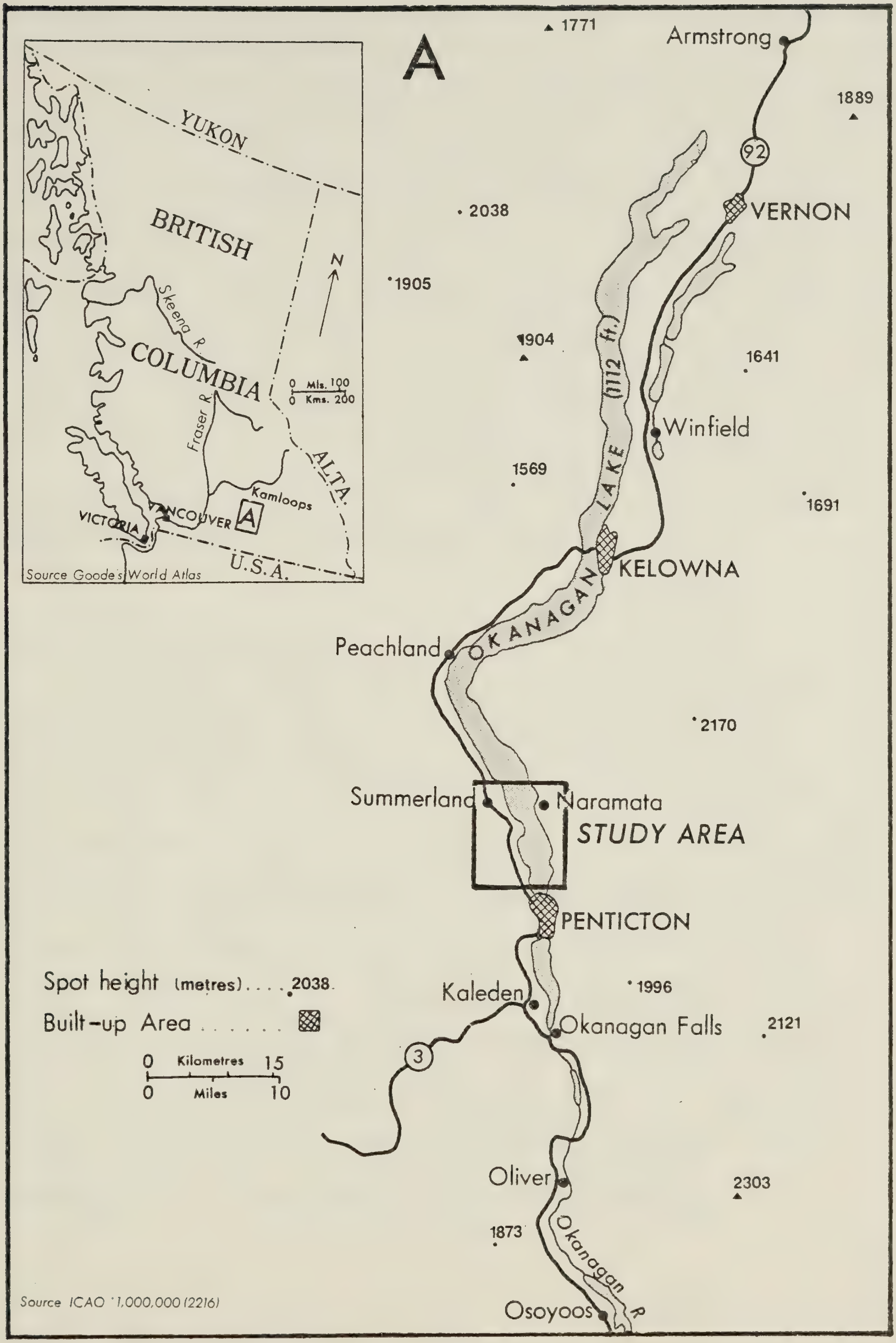


Figure 1-2 **Study Area Location**

1.4.1 Historical Geology

Kelley and Spillsbury (1948) outline the following geologic events for the Okanagan Valley. During the early Tertiary, the Interior Plateau was a flat, poorly-drained, marshy plain. Uplift and volcanic activity occurred during the Miocene. Extensive faulting and folding in the Tertiary times produced the present valley trend and its trench-like character. In conjunction with the development of the trench, the Okanagan Valley became the drainage system for the Shuswap Lakes and by the close of the Tertiary, the Okanagan was an established river valley.

1.4.2 Glacial History

The Okanagan region was subjected to a succession of glacial conditions throughout the Pleistocene, however, in this study only the events of the late-Wisconsin glaciation are considered. Ryder (1972, table 1, p. 79) suggests that within the Fraser Glaciation of the late Wisconsin, a major advance, the Vashon Stade, covered the interior between 13000 - 18000 years BP. No mention is made of an inter-stade in the interior coinciding with the Everson inter-stade of the adjacent Fraser lowland. However, Ryder does propose a late-glacial re-advance in the interior corres-ponding to the Sumas Stade of the Fraser lowland.

Nasmith (1962) describes the surficial deposits produced during the recession of the late-Wisconsin ice. He proposes that ice advanced (although which advance is being referred to is not specified) from the Monashee mountains to the east and the coast mountains to the west. The Monashee ice is thought to have filled the Okanagan Valley causing extensive erosion as it flowed southward. A later ice-sheet is believed to have covered southern British Columbia to a elevation in excess of 2130 m (Nasmith, 1962).

The deglaciation pattern for the Okanagan Valley, and other valleys of British Columbia is outlined by Flint (1935); Mathews (1944); Nasmith (1962); Fulton (1965, 1969, 1975) and Ryder (1972). Fulton (1975) proposes that the ice disappeared from the uplands with tongues of stagnant ice downwasting in the valleys. He presents a detailed summary for lake developments in the interior (table IX, p. 37). In the Okanagan Valley, glacial Lake Penticton formed when a plug of outwash and stagnant ice blocked the north-south drainage at McIntrye Bluff (fig. 1-3). The site of the ice-dam was identified by a north-south trending spillway channel carved in bedrock at 200 m above the valley floor (Flint, 1935, p. 113). As the ice receded, glacial Lake Penticton extended from McIntyre Bluff to Armstrong (fig. 1-2) and reached a maximum height of 500-530 m a.m.s.l (Nasmith, 1962, p. 42). Lacustrine sediments were deposited in Lake Penticton in deltas and as bottom

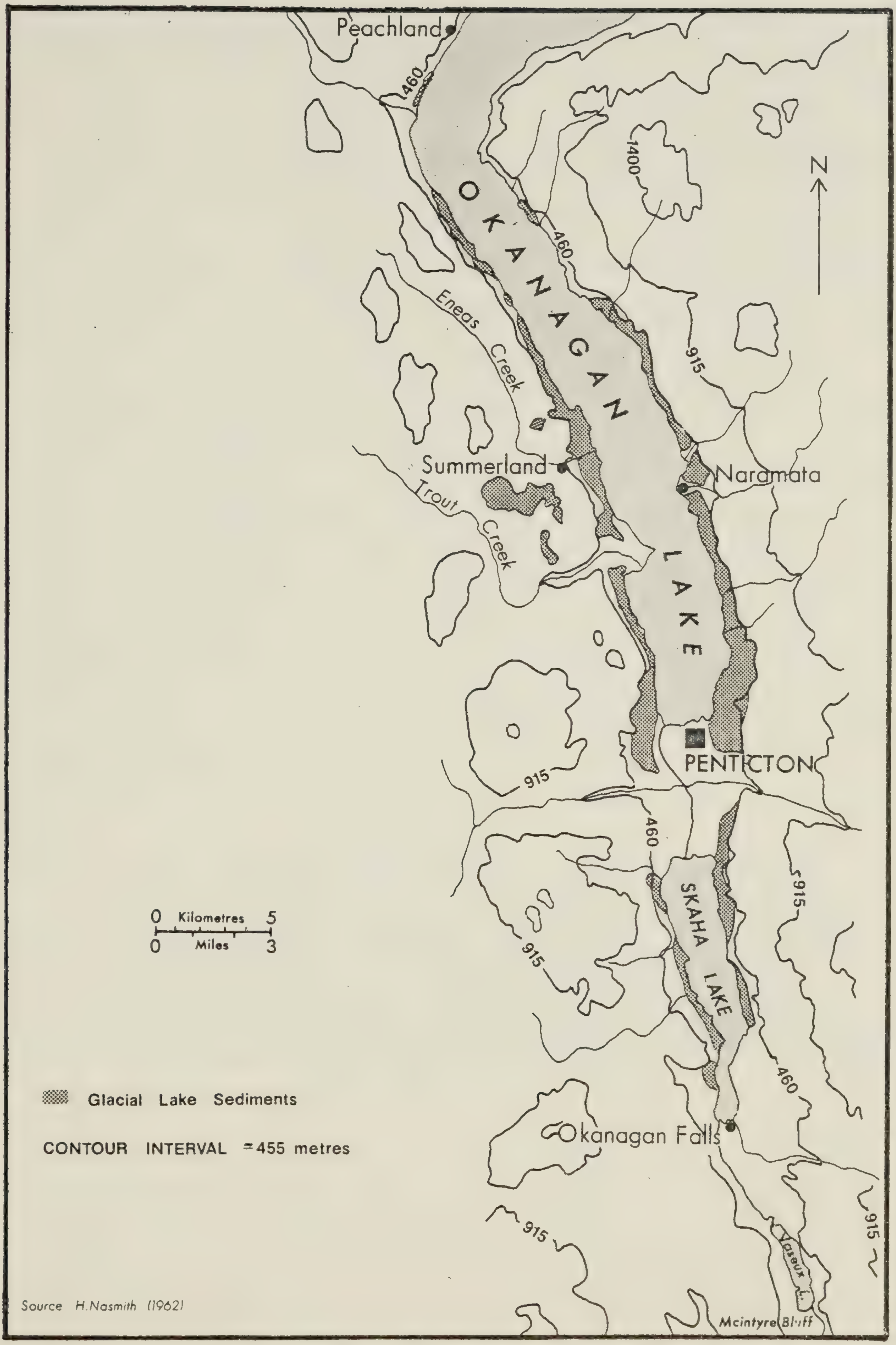


Figure 1-3 **Physiography and Glacial Lake Sediment Distribution**

deposits until Lake Penticton drained to the south. Additional information on Okanagan Lake's sub-surface morphology, and by inference its deglaciation sequence, has been gained from studies conducted by the Okanagan Study Committee.[1] A submerged terrace was located by echo-sounding approximately 15 m below the present lake level. This terrace was found on both sides of the valley from Squally Point to the south end of Skaha Lake (Okanagan Study Committee report 18, p. 10). The lower terrace level could indicate the original lake level following the draining of Lake Penticton. Additional information (D. Kvill, pers comm), suggests that with isostatic uplift and an increased volume of water originating from the North Okanagan and the Shuswap region, the present lake level was reached and wave action formed the present base of the upper terraces.

1 The committee was part of the Canada-British Columbia Okanagan Basin Agreement Study. This comprehensive study was initiated during 1971 to elucidate the chemical, biological and physical limnology of the five main-stem lakes in the Okanagan Valley - Okanagan, Kalamalka, Wood, Skaha and Osoyoos. The data collected would be used to determine the future water resources under different management alternatives.

1.4.3 Definition of the Study Area

The glacial lake sediments of the Okanagan Valley have been mapped by Nasmith (1962) who found them to vary in both size and quantity (fig. 1-1). However, the sediments along the shores of Okanagan Lake north of Penticton to Summerland and Naramata form the highest and best exposures (fig. 1-4). Seven sections were chosen for examination in this area, three on the east side of the lake and four on the west side (fig. 1-4).

1.5 Approach and Methods

Two main techniques may be used to study the depositional environment of glacio-lacustrine sediments; one is the study of sedimentation in active glacial lakes, the second, stratigraphic interpretation of exposed glacio-lacustrine sediments. These two techniques are summarized below:

1.5.1 Sedimentation Studies in Modern Glacial Lakes

A number of researchers have studied glacio-lacustrine sedimentation processes in present glacial lakes in western North America. Johnston (1922) studied the sedimentation processes active in Lake Louise, Alberta. Mathews (1956) identified underflow events responsible for lacustrine sedimentation in Garibaldi Lake, British Columbia.

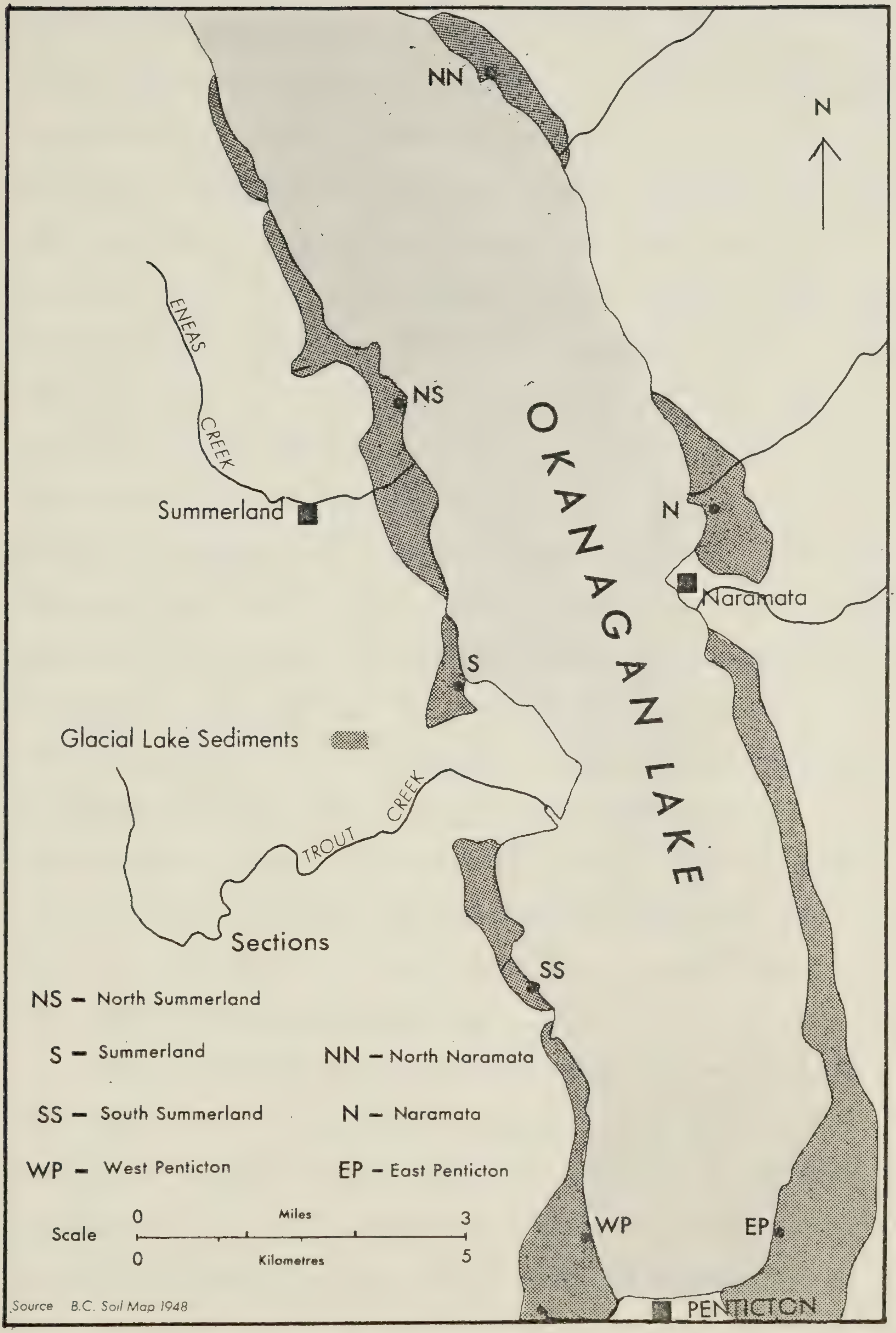


Figure 1-4 Indicates the location of the sections logged and analyzed.

Gustavson (1972) studied turbidity currents issuing from subglacial and englacial streams in ice-marginal Malaspina Lake, Alaska. Gilbert (1973) identified thermal structure as a significant manifestation of flow conditions and the distribution of the sediment in Lilloet Lake, British Columbia. Patterns of sediment inflow, physical limnology, and processes and mechanisms of sediment distribution have been examined. Utilizing water temperature profiles, inflowing stream discharge data, suspended sediment concentrations, echo-soundings, bottom core sampling, and grain-size analysis of bottom samples, the above mentioned authors, with the exception of Johnston (1922), have identified the significant role of underflows (turbidity currents), interflows and overflows in sediment distribution. These active mechanisms of sediment distribution are thought to be responsible for varved deposits. Johnston (1922) found that average varve thickness in Lake Louise, Alberta corresponded to sediment inflow. Since underflow was not detected, (by Johnston) deposition from suspension by interflow and overflow was postulated.

Mathews (1956) identified underflow and overflow in Garibaldi Lake; low inflow of sediment with low concentration of suspended clay minerals, produced graded-beds of fine sand on the lake bottom. Gustavson (1972) observed continuous underflows associated with the deposition of

varved sediments. Graded and cross-bedding structures were found in the summer layers, but not in the winter laminae which were deposited from suspension. Gilbert (1973) identified varved sediments resulting from interflows and underflows. Varve thickness was correlated to annual inflow, and lamination within individual varve units was related to intermittent or single-pulse underflows.

Study of present-day glacial lakes can assist in the determination of the frequency, magnitude and movement of suspended sediment by turbidity currents. But, studies in active glacial lakes have not, as yet, provided a complete understanding of how mechanisms of sediment entrainment, transport, deposition and formation of structures occurs by turbidity currents. It is possible that the significance of turbidity currents could be assessed from Pleistocene or ancient turbidite sediments by interpretation of sedimentary processes (see Chapter II).

1.5.2 Environmental Interpretation of Pleistocene Lacustrine Sediments

This study involves the use of environmental interpretation to analyze the depositional environment of glacio-lacustrine sediments. Through detailed observations of sedimentary associations the properties of sediments, energy conditions at the time of deposition, and the directional properties of the depositing fluid, an under-

standing of the complex interrelationships of ice-contact landforms can be achieved based upon fluvial-sedimentary processes. A similar approach can be utilized for lacustrine environments where unidirectional currents (turbidity currents) are significant. Harms and Fahnestock (1965) propose that the relation of stratification to flow regime can be utilized by considering typical turbidity current deposits described by Bouma (1962) and Walker (1967). (A discussion of turbidity currents, turbidite division, and flow regime in the formation of varved sediments follows in Chapter II and III.) This approach used here is to interpret the depositional processes and determine the paleo-environment of the lacustrine sediments within the southern Okanagan Valley by observation and measurement and by recording both lateral and vertical distributions of the sidement types.

CHAPTER II

THEORY ON THE ORIGIN OF VARVES

2.1 Early Hypothesis on Varve Formation

According to Flint (1971), as early as 1769 the regular alternation of sedimentary couplets in stratigraphic sections were attributed to an annual rhythm of deposition. De Geer (1912) applied the Swedish word 'varv", meaning 'periodic repetition', to distinguish glacio-lacustrine rhythmites that were deposited in one year. However, depositional processes in different environments have also been responsible for varved sediments (see Anderson and Kirkland, 1966; Duff, Hallam and Walton, 1967). A comprehensive definition for the term varve has been proposed by Gilbert and Shaw (1974),

> ... "the term varve can be used to distinguish any sedimentary deposit on the basis of colour, texture, organic or inorganic composition, or minerology that has been deposited in one year."

Their definition has been followed in the present study. De Geer (1912) concentrated his study on glacio-lacustrine varves as a geochronological tool for dating ice-recession in Scandinavia. He argued that sediment-laden meltwaters entered glacial lakes as underflows during the summer. The coarse sandy or silty sediment forms the so-called summer laminae, while the fine silts and clays circulate throughout the lake by turbulence and settle out of suspension

during the winter. De Geer supported his hypothesis by observation of differing varve thicknesses caused by relief features on the beds of former lakes. Varves were thicker on the proximal side of bedrock highs. He interpreted this as an indication that the highs affected sedimentation and therefore, bottom currents must have been active.

Antevs (1925) utilized De Geer's geochronological techniques in dating ice-retreat in eastern North America, though he disagreed with De Geer's hypothesis on varve formation. Antevs proposed that glacio-lacustrine varves were formed by sediment-laden meltwaters dispersing sediment throughout the lake on, or just below, the lake surface. The coarse sediments were considered to fall-out of suspension first and the fines following the freezing of the lake surface. Antevs suggested that less dense meltwater could not flow below the dense thermal stratification zones found at the bottom of glacial lakes. Observations by Johnston (1922) in Lake Louise, Alberta and experimental work on settling velocities of sediment in glacial lakes (Kindle, 1930) supported Antev's theory. However, Antevs and other early researchers failed to consider that in-flowing meltwaters containing a high suspended sediment concentration is commonly of higher density than the lake water and could plunge below, as well as in-between the lake water, and flow along the bottom of the lake displacing the lighter ambient lake water. The presence

of the current structures in lake bed sediments cannot be explained by Antevs. Recognition of turbidity currents (Kuenen, 1950, 1951) and their significant role in the formation of graded beds (as in flysch and greywacke formation), seems to confirm the validity of De Geer's hypothesis (Gustavson, 1972; Gilbert, 1973). It appears then that the role of turbidity currents in glacial lakes as under, over, or interflows can more readily account for the deposition of varved sediments.

2.2 Turbidite Origin of Varves

A turbidity current (a type of gravity current) can flow over, into or under a body of water it enters, depending upon the differences in density of the current and the ambient fluid. Observations in Lake Mead reservoir led to the identification of three types of turbidity currents: overflow, interflow and underflow (Gould, 1951). Gould found that overflows and interflows occurred during periods of low concentrations of suspended sediment in the inflowing water, while underflows were identified as the dominant currents in depositing sediment when large discharge peaks brought high concentrations of suspended sediment into the reservoir. In addition, other researchers (Gilbert, 1973, Gustavson, 1972) have found that sediment concentration in the ambient lake water is also important. Lake water containing greater sediment concentration will be denser and underlie less dense layers of water with

smaller concentration. Overflow, interflow, or underflow therefore will largely be determined by the differences in suspended sediment in the lake, and the sediment concentration in the inflowing water. The following is a brief discussion on the role of sediment deposition by over, inter and underflow turbidity currents. A more detailed discussion on the fluid dynamics of turbidity currents may be found in Bell (1942), Allen (1970), Middletion (1966 a,b; 1967), and Walker (1967).

2.2.1 Overflow

Overflow is the movement of a more or less discrete sediment laden flow of water over the surface of another water body. The inflowing water and sediment mix is lighter than the ambient water body. As the current spreads over the lake (controlled by a number of factors; delta configuration and size, lake basin morphology, winds, and circulation patterns within the lake) a loss of velocity occurs followed by sediment deposition. Only silt and clay size particles are carried by this type of current (Gilbert 1973). The coarest grains will be deposited on the prodelta slope with the proportion of fines increasing distally. The fine clay size particles may be kept from settling by turbulence and by a high density of particles suspended in the lake. With the freezing of the lake surface these particles will settle out of suspension. Therefore, varves formed from overflow currents exhibit a graded coarse summer layer of silt, overlain by a winter layer of clay. These varves

sometimes exhibit laminations. Antevs (1951) suggests that these could be the result of diurnal fluctuations, a reduction of sediment to the lake, and rapid loss of velocity by the current. Laminations in the winter layer may be the result of melting and the influx of coarser sediment. Also, overflow sedimentation in large lakes will exhibit a thicker clay (winter) layer and thinner coarse (summer) layer distally from the sediment source.

2.2.2 Interflow

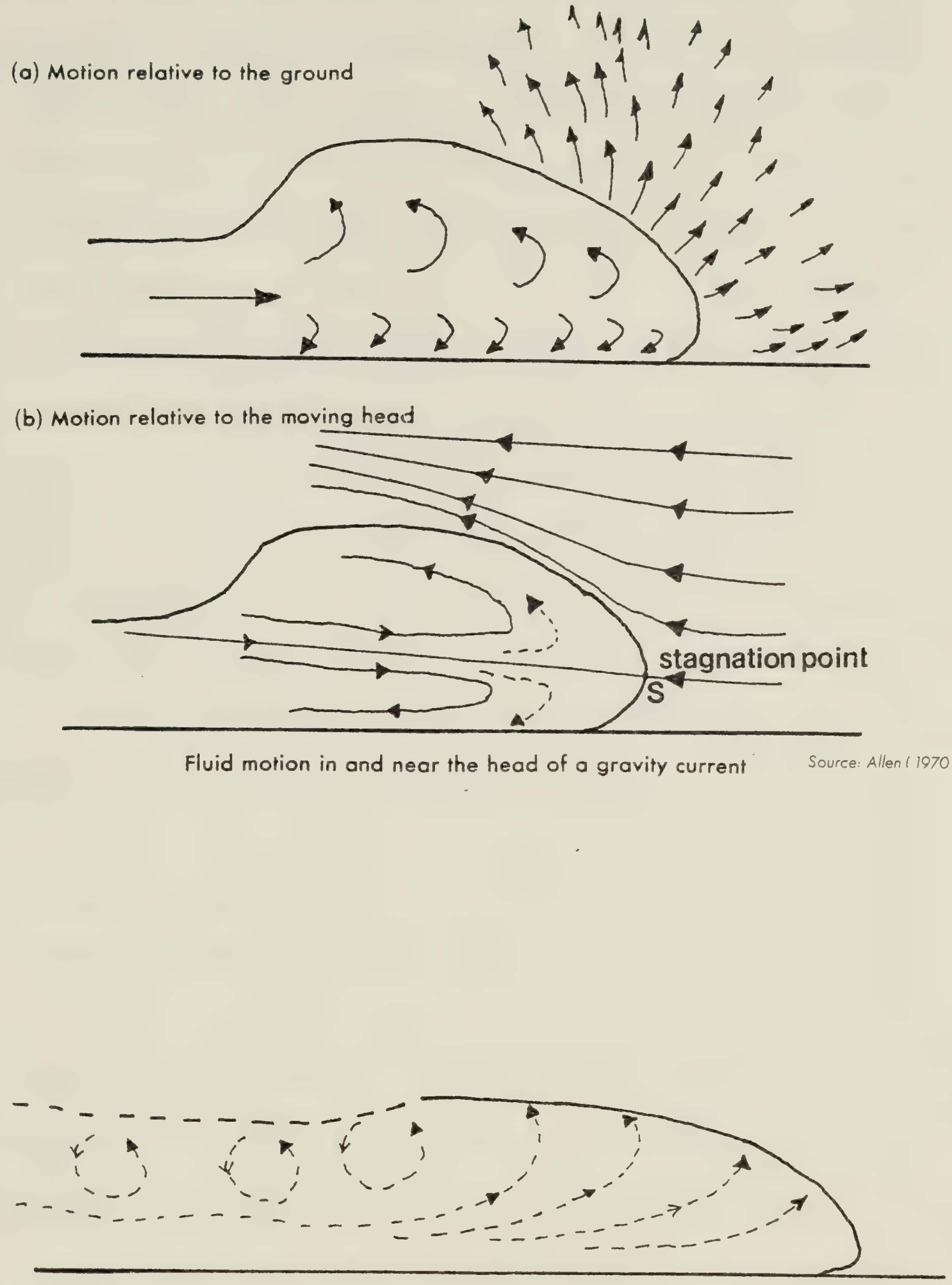
Interflows are inflowing currents denser than the lake surface water, but less dense than the lake bottom water. This type of current will seek a level at which lake water density equals its own. As in overflow, temperature effects or sediment concentration could produce this type of current. Interflow currents rapidly lose velocity as they move into the lake (Gould, 1951). Coarse particles will tend to settle-out rapidly close to the current source, but they may be carried further due to greater turbulence. Dilution of the current by mixing lake water will aid in reducing sediment transport. Current velocity decreases as energy is lost to frictional resistance along the interface between the interflow and ambient fluid. As with overflow, this type of current will transport only fines. With the loss of coarser sediment proximally, the diluted interflow will rise to the surface causing dispersion of clay particles into the ambient water until freeze-up. Varve

morphology will be similar to that resulting from overflow sedimentation; coarse summer layers of silt and a distinct clay (winter) layer.

2.2.3 Underflow

Unlike over or interflows, suspended sediment concentrations in underflows are large enough to negate temperature differences in lakes. As Bell (1942) states, the driving force of turbidity overflows and interflows is the initial velocity of the inflowing stream and once velocity is reduced because of decreased gradient, competency is also reduced and deposition takes place. However, the weight of suspended sediment in underflows causes a hydraulic head to drive the current. Kuenen (1950) suggests that the main factors determining the velocity of turbidity (by inference an underflow) current are size, density, slope, viscosity and resistance (bed and ambient fluid). As Allen (1970) summarizes, the greater the slope the greater is the velocity head as indicated by the elevation of the head of the current (fig. 2-1a) relative to the elevation of the source of suspended sediment.

Middleton (1966 a, 1966 b) observed that a wave is established behind the current head immediately upon the stream entering the lake and becomes the major source of sediment (fig. 2-1c). He also confirmed that maximum velocity is attained in this wave and not in the head as thought by Kuenen (1950). Middleton's (1966 a, 1966 b)



(c) Pattern of flow within a turbidity current head. Source: Middelton, (1966)

Figure 2-1 Showing fluid motion outside and within an underflow.

flume experiments also indicated that flow is diverted outwards from the interface of the head and ambient fluid (fig. 2-1a). This allows the current head to overcome the resistance of the ambient fluid, and the leading point of the head becomes a stagnation point. Within the head the flow is diverted upward (fig. 2-1c). This upward divergence of flow also forms eddies behind the head and flowlines are forced backwards by the viscous drag (fig. 2-1b). The eddies are formed when fluid from the ambient medium mixes into the current. Middleton (1966 b) refers to this as the mixing zone. Denser fluid from the wave moves into the head maintaining the size and shape of the head and causing an unsteady surging motion. Middleton also provided evidence that turbidity currents entrain and flow over horizontal lake bottoms. Passage of the wave followed by a sudden decrease in velocity causes deposition of the coarse particles on the lake bed. At the tail of the current only fine silt and clay are left to settle-out by suspension. However the following section discusses the modes of deposition by underflows based on flume experiments by Kuenen and Migliorini (1950); Middleton (1966 c).

2.2.4 Deposition of Graded Bedding by Turbidity Currents

Kuenen and Migliorini (1950) used sand and mud suspensions to produce graded bedding from turbidity currents in flumes. Their experiments produced rapid deposition of the sediment resulting in a thin graded bed. However, the mode

of sediment deposition was not observed. Middleton's (1966 c) flume experiments provided observations on sediment deposition by underflows of differing sediment concentrations. In underflows of low concentration the following occurred:

a) slow deposition behind the head, with no traction of particles;
b) slow deposition, but traction resulting from increased bed roughness;
c) rapid deposition and an accompanying rapid decrease in velocity of the current;
d) deposition of fines from the tail of the current.

The bed formed from low concentration flows exhibited vertical and horizontal grading, with fining upwards and distally from the flow source.

In high concentration flows Middleton (1966 c) observed the following deposition of sediment:

a) slow deposition, but shearing and traction of particles;
b) a mass settling of particles forming a "quick bed";
c) formation of a plane bed, with no deformation by shearing;
d) deposition of fines from the tail of the current.

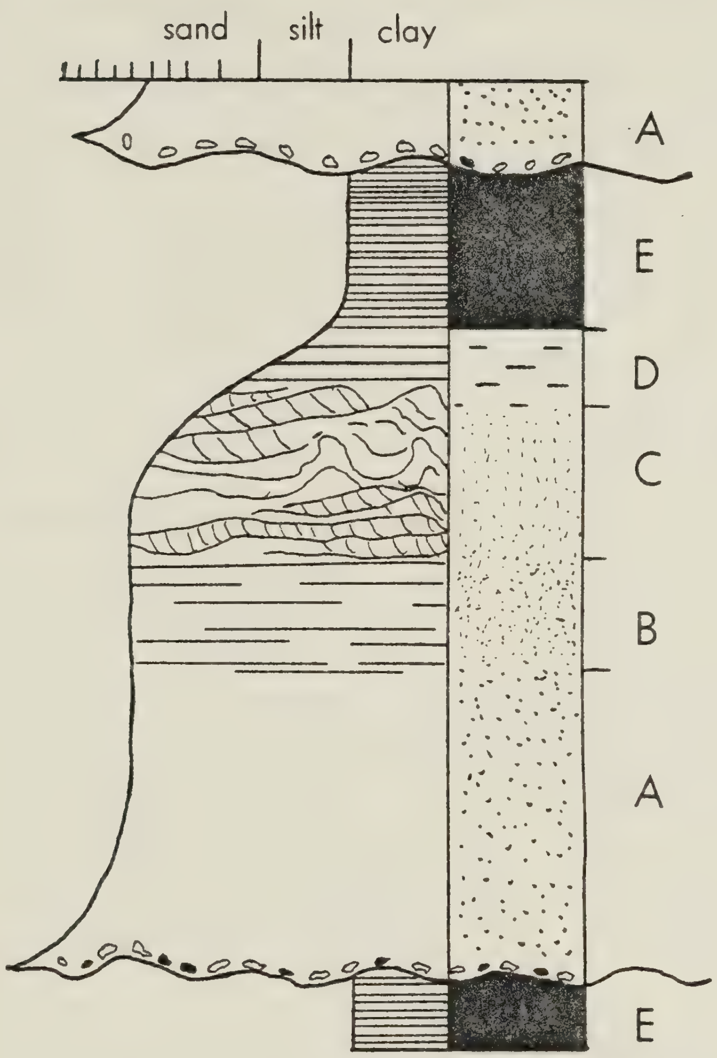
Middleton's experiments clearly demonstrate that graded bedding occurs vertically and horizontally. However, because of the small-scale experimental size of the flume, cross-bedding, sole marks, cross-lamination and flute stratification elements found in ancient turbidite structures and Quaternary lacustrine stratigraphic units were not reproduced.

An important consideration is necessary when interpreting ancient marine turbidites. Turbidity flows were of large dimensions and are unlikely to be duplicated in ice-marginal or proglacial lakes. However, small Pleistocene ice-marginal and proglacial lakes would certainly have been subjected to turbidity currents of greater magnitude than those found in present day glacial and ice-marginal lakes (Mathews, 1956; Gilbert, 1973; Gustavson, 1974).

2.3 Ancient and Recent Turbidites

Ancient turbidites (especially flysch deposits) reflect the alternating cyclic sequence of coarse and fine beds deposited by turbidity currents (Bouma and Bower, 1964; Duff, Hamlam and Walton, 1967; Walker, 1967). Bouma (1962) proposed an ideal turbidite interval (fig. 2-2). As the current wanes in velocity, the graded bedding passes from coarse gravels vertically into the sand and silt divisions. Although the magnitude of the currents and size of the flysch deposits make comparisons with glacio-lacustrine varves very tentative, Lajtai (1967) and Banerjee (1973) present arguments for the turbidity current origin of glacio-lacustrine varves.

Kuenen (1951) described the significant role of turbidity currents in the formation of glacio-lacustrine varved sediments. He supported De Geer's (1912) original hypothesis of underflows as the active process in the



A—Graded division - coarse gravels and sands

B—Lower parallel - lamination division - coarse and medium sands

C—Current ripple - lamination division - fine sands

D—Upper parallel - lamination division - silt and clay laminae

E—Pelitic division - mud, silt and clay grain size

Source Selley (1970)

Figure 2-2 Turbidite Sequence (modified from Bouma, 1962)

formation of the summer laminae. Studies in modern glacial lakes have identified turbidity currents, underflows, overflows and interflows, as the active processes in the formation of lacustrine varved sediments (Mathews, 1956; Gustavson, 1972; Gilbert, 1973). Stratigraphic evidence of glacio-lacustrine varved sediments as noted by Lajtai (1967), and Ashley (1975), support Kuenen's hypothesis. Agterberg and Banerjee (1969, p. 647) provide a succinct summary of the processes active in the formation of most glacio-lacustrine varves:

> "... a varve couplet has three genetically dissimilar parts (1, 2a and 2b):
>
> 1. The silt (summer part was deposited in a relatively short period by turbidity current. Variations between successive layers may be strong and a single layer will show a strong decrease in thickness away from the source. When multiple graded units are present, this may mean successive turbidity currents generated in the same year or pulsations within a single turbidity current.
>
> 2. The clay (winter) layer consists of two parts: Part 2a deposited by the turbidity current after stagnation, and 2b deposited by slow, continuous settling from suspension."

2.4 Turbidite Flow Regime

Walker (1967) incorporated results or turbidity current experiments (Middleton, 1966, b) with the flow regime proposed by Harms and Fahnestock (1965). This is shown in figure 2-3. Walker suggests that flow regime can be interpreted from facies, depending upon the distance travelled by the current across the basin floor, the magnitude of the floor gradient, and the flow parameters of individual

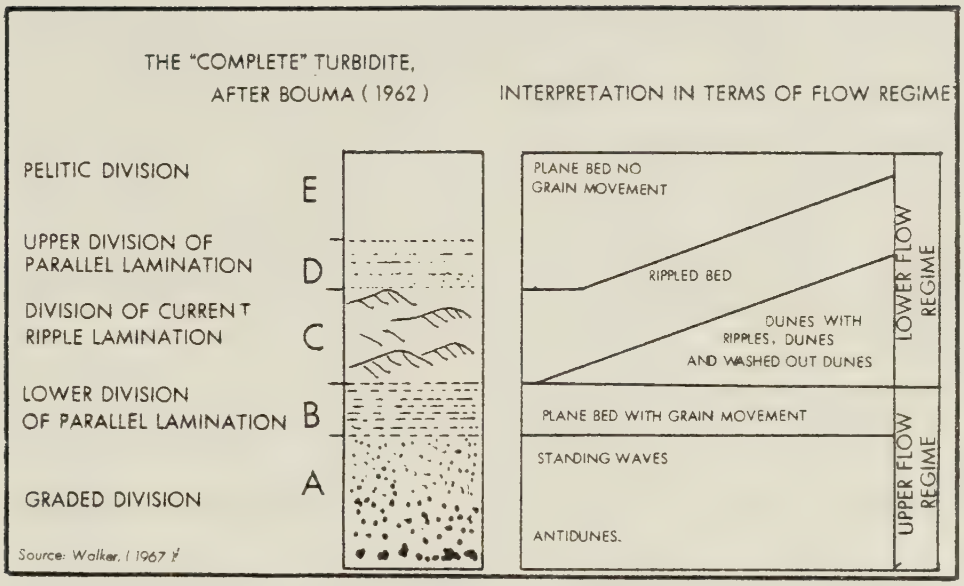


Figure 2-3 **Bouma's complete turbidite and it's interpretation by analogy with flow regimes of Simons and others (1965).**

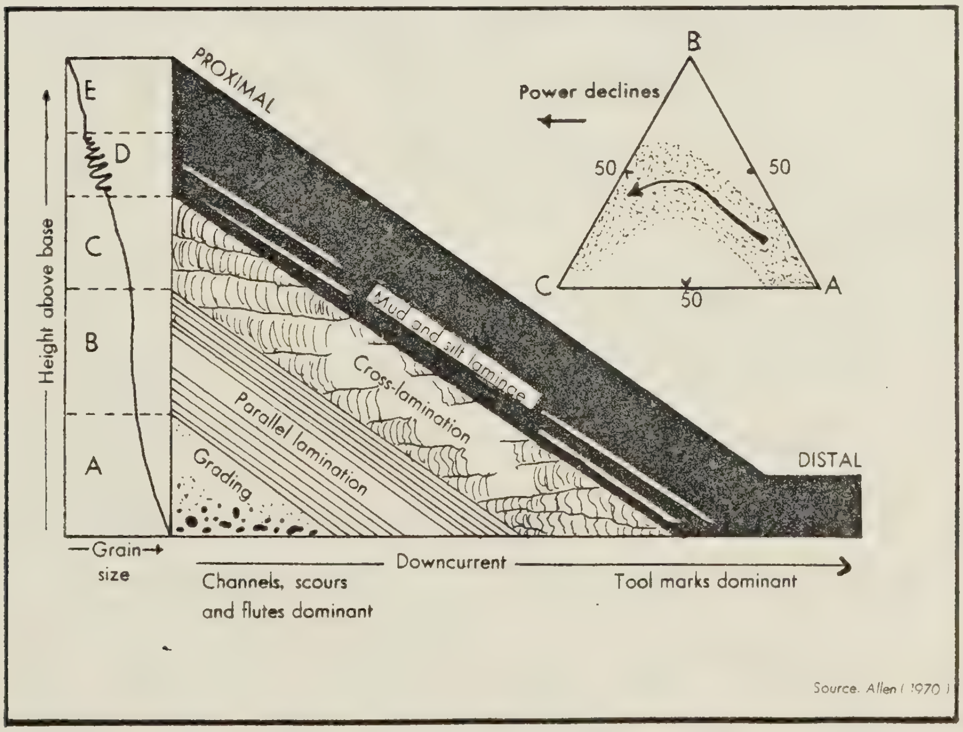


Figure 2-4 **Vertical and lateral (downcurrent) variation in an ideal turbidite bed (partly after R.G. Walker).**

currents. He attributed differences in facies status between proximal and distal turbidites to the direct or indirect result of grain segregation processes within currents. Two mechanisms of sediment distribution are proposed: lateral grading and traction-carpet. No lateral grading occurs on steep slopes as coarse sediment is transferred rapidly into the current head. However, as the current moves over lower slopes across the basin floor, the head and current stream are of the same velocity; sand will be deposited first, followed by fines out of suspension. The result is a lateral graded bed. In the traction-carpet mechanism, the coarse sediment is moved by bedload transport. Within the upper-flow regime, a high shear stress reduced below a critical level will cause the sediment carpet to 'freeze', with shear stress removing only the top layer. The result will be poorly graded or an ungraded bed (division A) deposited in a proximal environment (figure 2-4). With low shear stress, within the lower part of the upper-flow regime, a gradual accumulation of sand will form a structureless or laminated bed (division B). Ripple-drift lamination occurs as current velocity decreases distally (division C). With a slow fall-out of sediment into the traction carpet, A type ripple drift (stoss side erosion, see Jopling and Walker, 1968) occurs; however, as the current decays, the greater fall-out of suspension forms B type ripple-drift (preservation of stoss-side) (upper C division).

Walker suggests two mechanisms forming laminae and cross-laminae directly by the current:

1. Reworking, by the current, of previously deposited sediment. The result is thin, ungraded bedforms with ripples forming a single set of cross laminae.

2. Formation of laminae and cross-laminae during primary deposition. The bedforms are thought to be thicker and better graded with ripples climbing into ripple-drift.

Walker (p. 35) states, "Primary deposition can occur in all environments, but reworking is more likely in proximal environments as the latter part of the turbidity current slows down through the regimes which form plane beds and ripple beds."

Walker's study is important as an aid in interpretation and understanding the depositional environment of the glacio-lacustrine varved sediments in the study area.

2.5 Conclusions

The graded-bedding of ancient marine turbidites is considered by geologists to have been derived from turbidity currents (principally underflows). However, the transport and deposition of sediment by turbidity currents are still not theoretically or experimentally well understood (Allen, 1970). Although small-scale experimental work (Middleton, 1966a, 1966b, 1967) and limited observations in lakes and reservoirs (Gould, 1950; Mathews, 1956; Gustavson, 1972; and Gilbert, 1973) have identified the ability of turbidity currents to flow over, into or under a fluid and to transport

and deposit sediment, the importance of any one particular process in the deposition of glacio-lacustrine varves seems to be unclear. However, with an increase in direct studies of the mechanics of sediment entrainment, transport and deposition by turbidity currents in active glacial lakes, and combined with environmental interpretation of stratigraphic lacustrine varved sediments, a greater number of inferences could be drawn on the genesis of lacustrine sedimentation by turbidity currents. Varves appear where both turbidity currents and settling sedimentation work together to produce the varve couplet.

CHAPTER III

METHODOLOGY

3.1 Introduction

A number of techniques were employed to distinguish the depositional environment of the glacio-lacustrine sediments of the Okanagan Valley. In the field the following were measured and recorded: geometry (shape and size of the stratigraphic units), texture, primary sedimentary structures, deformation structures, and directional properties obtained from cross-lamination. The results of the field measurements are presented in figures 4-9 and 4-10 inclusive.

Mechanical analysis was conducted in the laboratory on samples taken at 10 cm intervals within a thick silt bed in each of the seven sections. Mean-grain-size and standard deviation values (Folk and Ward, 1957) were determined from the results of pipette analysis. The results are plotted in figure 4-13 to 4-16 inclusive.

A linear correlation computer program adopted from Anderson and Kirkland (1966) by A. Higgins, Department of Geography, University of Alberta,[1] was used to correlate the varves in all seven sections. The technique is discussed in section 3.7, and a copy of the program is contained in Appendix 1. However, problems in the correlation of the varves were discovered following the results; these are fully discussed in section 4-7.

3.2 Geometry

The overall shape of a sedimentary body is a function of pre-depositional topography, the geomorphology of the depositional environment and its post-depositional history (Selley, 1970). For large sedimentary bodies of uniform lithological character, the shape is often preserved. The geometry of a sedimentary body reflects the controls present in the depositional environment and is therefore useful in the analysis of sedimentary environments. In glacial environments, bodies of ice are often the controlling element. The geometry of any sedimentary body may be subdivided into two categories; external and internal.

The external geometry of the southern Okanagan silts reflect the following depositional history: development of, and rapid sedimentation into, an ice-marginal lake, and the post-depositional exposure and development of the silt terraces with falling lake levels. The controlling element is assumed to have been a large down-wasting glacier occupying the trench, with ice-marginal lakes formed between the ice and the valley sides (Flint, 1935; Nasmith, 1962). In the study area, the external geometry was measured, recorded and photographed, and the results are discussed in section 4.2

[1] This program was modified by Higgins in order to examine varve sequences in the Edmonton area, Alberta, where large numbers of varve sections had to be correlated over a wide geographical region. The technique seemed appropriate for the present study.

Internal geometry includes stratification and fabric within the sedimentary body. Interpretation of the internal geometry of the glacial lake sediments is discussed in greater detail under section 3-4.

3.3 Texture

The textural properties of a sedimentary body are of considerable environmental significance. Texture refers to the size, shape and natural arrangement of the component grains (Laporte, 1968). For clastic sediments, such as the lacustrine sediments in the study area, the environment in which they were deposited and the depositional processes are reflected in the texture of the sediments. The sediments found in the lower parts of the sections are generally coarse-grained, angular and well-sorted, and indicate rapid deposition in a proximal environment. However, fine-grained deposits also occur in lower parts of the sections. The upper parts of the sections are composed of fine-grained, laminated deposits suggesting distal deposition in quiet water.

The vertical and lateral changes in texture of the sediments reflect closely the B, C, D, and E divisions of the turbidite division (fig. 2-2). The texture of the sediments was visually assessed in the field, and is incorporated with the facies states (fig. 4-8).

3.4 Particle Size Analysis

Statistical analysis of grain-size distribution curves has been used to determine depositional environments (Folk and Ward, 1957; Solohub and Klovan, 1970). Given that all grades are available, the coarser the grain-size the higher the energy level of the depositing current. Fluvio-glacial sediments show a rapid lateral and vertical fluctuation in grain-size distribution and in sorting properties - characteristics also evident in glacio-lacustrine turbidites. Evidence of a single, or multiple, coarse to fine grain-size fluctuation in the vertical profile could indicate deposition by one or more turbidity currents. In addition, changes in grain-size within a unit can help identify the processes responsible for deposition (Ashley, 1975). Mechanical analysis of the samples was performed following a procedure based on the following standard sizing analysis (Ackroyd, 1957):

Pretreatment

No organic material was found in any of the samples and mechanical disaggregation was not necessary since the field samples were already finely divided.

1. Samples were oven-dried at 105°C for 24 hours.
2. 10 g of material was weighed and 2 ml of 2.0 percent sodium hexametaphosphate was added to achieve clay disaggregation.
3. The solution was mixed for 5 minutes using an electric mixer.
4. The sample was wet-sieved through a 0.063 mm sieve; as less than 5 percent was retained in the 0.063 mm sieve no dry-sieving of coarse fractions was necessary.

Sedimentation of the silt and clay percentages

5. The fines were poured into a sedimentation cylinder and the solution was brought up to 1000 ml by the addition of distilled water.
6. The cylinder and its contents were placed in a constant temperature bath at 30°C.
7. Before sedimentation was allowed to proceed, the contents of the cylinders were stirred for a period of 2 minutes to ensure homogenous mixing of all particle sizes.
8. A 10 ml sample was taken by pipette at a depth of 10 cm below the meniscus. Sampling times of 22 secs., 1 min 30 secs., 6 mins, 24 mins, 1 hr and 30 mins, 6 hrs 30 mins, and 25 hrs 25 mins, were used to give sampling points from 4Ø to 10Ø at 1Ø intervals.
9. The 10 ml samples were oven dried at 105°C and weighed.
10. The proportional size fraction percentages of the original pre-treated samples were calculated. Folk and Ward (1957) statistics of mean grain-size and standard deviation were used to illustrate grain-size changes within each silt laminae.

3.5 Sedimentary Structures

Allen (1970) states that sedimentary structures give some indication of the depositing flow, velocity, and direction of the currents which occur in sedimentary environments. A large number of sedimentary structures have been described and classified on the basis of morphology (Pettijohn and Potter, 1964). Experimental work in flumes and studies in presently active environments have shown that sedimentary structures result from bedforms developed under varying flow conditions. Harms and Fahnestock (1965, p. 87) state,

> "...that bedforms are a function of the following variables (and possibly others): depth, slope, particle-size and shape, particle sorting, specific gravity of grains, density and viscosity of the water-sediment mixture, and cross-sectional shape and alignment of the channel."

Simons, Richardson and Nordin (1965) demonstrate that these different combinations of hydraulic and sediment variables can produce a sequence of bed configurations in alluvial channels. They found that bedforms develop as the tractive force increases beyond the threshold value for sediment entrainement. If the tractive force is balanced by the friction between the fluid and the bed, a plane bed results. However, with increasing tractive force, the initial plane bed gives way to a sequence of ripples, ripples-on-dunes, plane bed, and antidunes (fig. 3-1).

In stratigraphic exposures, primary sedimentary structures exhibit internal stratification. Several authors have described and related these structures to processes and environments of deposition (Allen, 1964; 1970a; Coleman and Gagliano, 1965; Jopling, 1963, 1966; Jopling and Walker, 1968). In the field, sedimentary structures were measured and recorded in the following manner:

1. The face of the units in the sections were cleaned and exposed where necessary.

2. In some cases, a fine spray of water was applied to the structures to aid in distinguishing the traces of the forsets of cross-bedding and cross-lamination.

3. The total thickness of each sedimentary unit was measured.

4. The lower contact of each unit was assessed as to whether a gradual, abrupt, irregular, depositional or transition occurred from the previous unit.

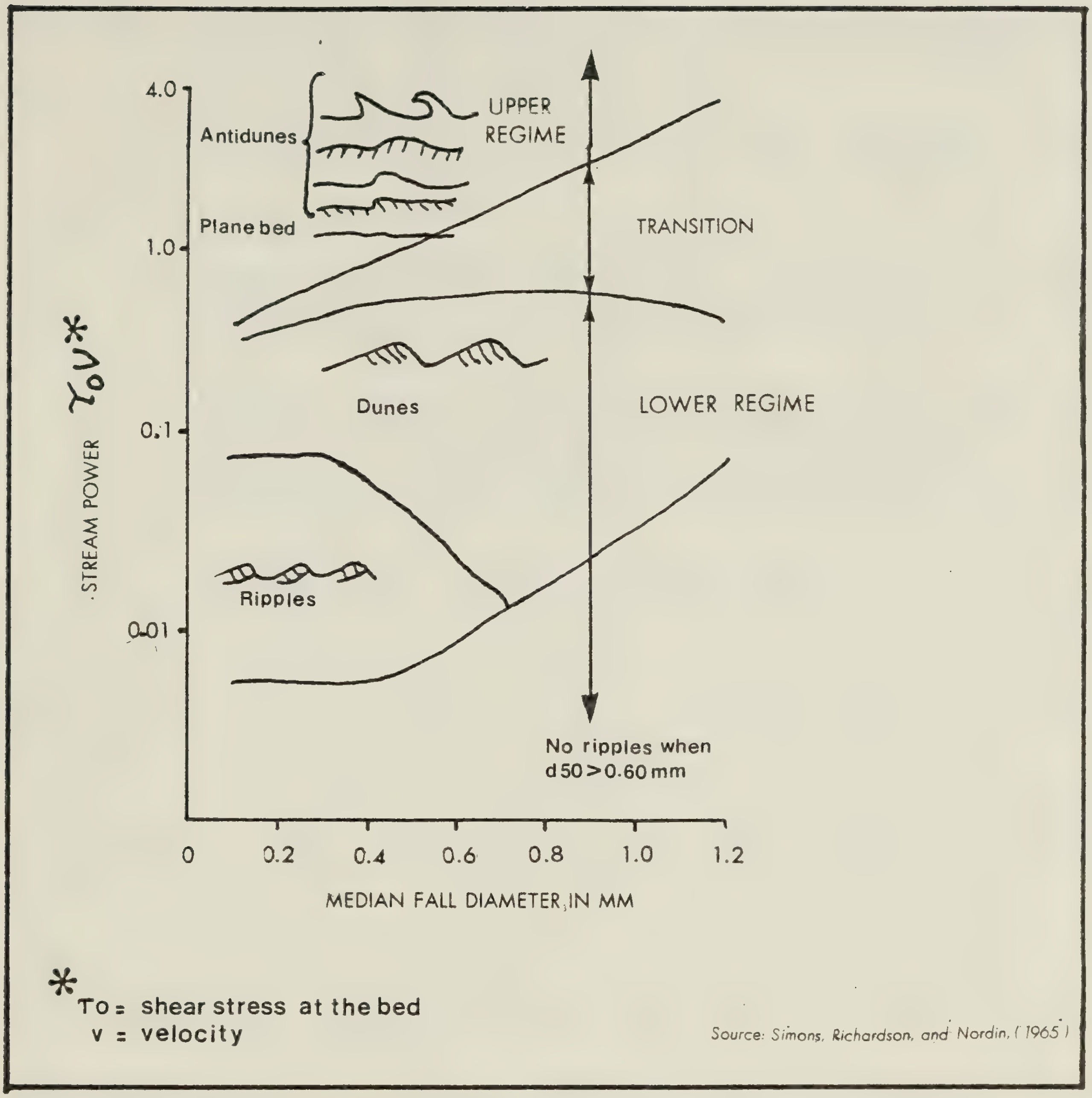


Figure 3–1 Relation of stream power and median fall diameter to form of bed roughness.

5. The lateral continuity for each unit was classified under the following criteria: extensive, continuous or discontinuous.

6. Any disturbance within a unit was recorded.

7. Field grain-size of the unit was assessed.

8. Where applicable, the internal structure of cross-lamination units were classified according to Jopling and Walker's (1968) nomenclature.

9. Height of individual sets within the unit was measured and recorded. Also, the angle of climb for B-type climbing ripple drift was taken tangentially from the bed through a line joining the rupple crests.

10. Paleocurrent directions were measured (see 3.5).

The sedimentary structures were assigned facies states following Shaw (1975). This aided in interpretation and allowed statistical treatment of the sedimentary characteristics; namely, the successional sequences. Transitions between facies states were enumerated from bed to bed vertically from the base of each section. The statistical treatment generated from this analysis is presented in Chapter IV (section 4.2).

Although much is known from flume experiments on the behaviours of fluid-sediment mix in formation of bedforms, the stratification elements generated from bedforms found in stratigraphic sections are useful in interpreting flow environments. It is necessary, if stratification type is to be used to interpret changing conditions of flow, and to relate bedform and stratification type. Harms and Fahnestock (1965) utlized the work on bedforms by Simons, Richardson, and Nordin (1965) to outline a flow regime concept (fig. 3-2)

in which stratification elements are used to interpret depositional flow environments. Although their study is concerned primarily with the relation of stratification to flow regime for fluvial environments, they outline the use of the flow regime concept for other environments. Harms and Fahnestock (1965, p. 109) state,

> "Assignment of sedimentary units to flow regime categories allows comparative, although generalized interpretation of depositional flow environment. This classification should be useful in any setting, fluvial or marine, with unidirectional currents."

They illustrated the use of stratification and flow regime in the interpretation of a typical turbidite deposit, (fig. 2-3). This aspect of their study was used by Walker (1967) to present a detailed study of facies change in tubidites (section 2.4).

3.6 Directional Properties

In reconstructing sedimentary paleo-geography, paleo-current analysis is a valuable technique. Pelletier (1965) states that from observation on current structures the direction of the paleo-slope and the direction of the sedimentary transport can be determined. Local relationships of current direction can be used in environmental interpretation, whereas regional interrelationships give valuable evidence of paleocurrent patterns.

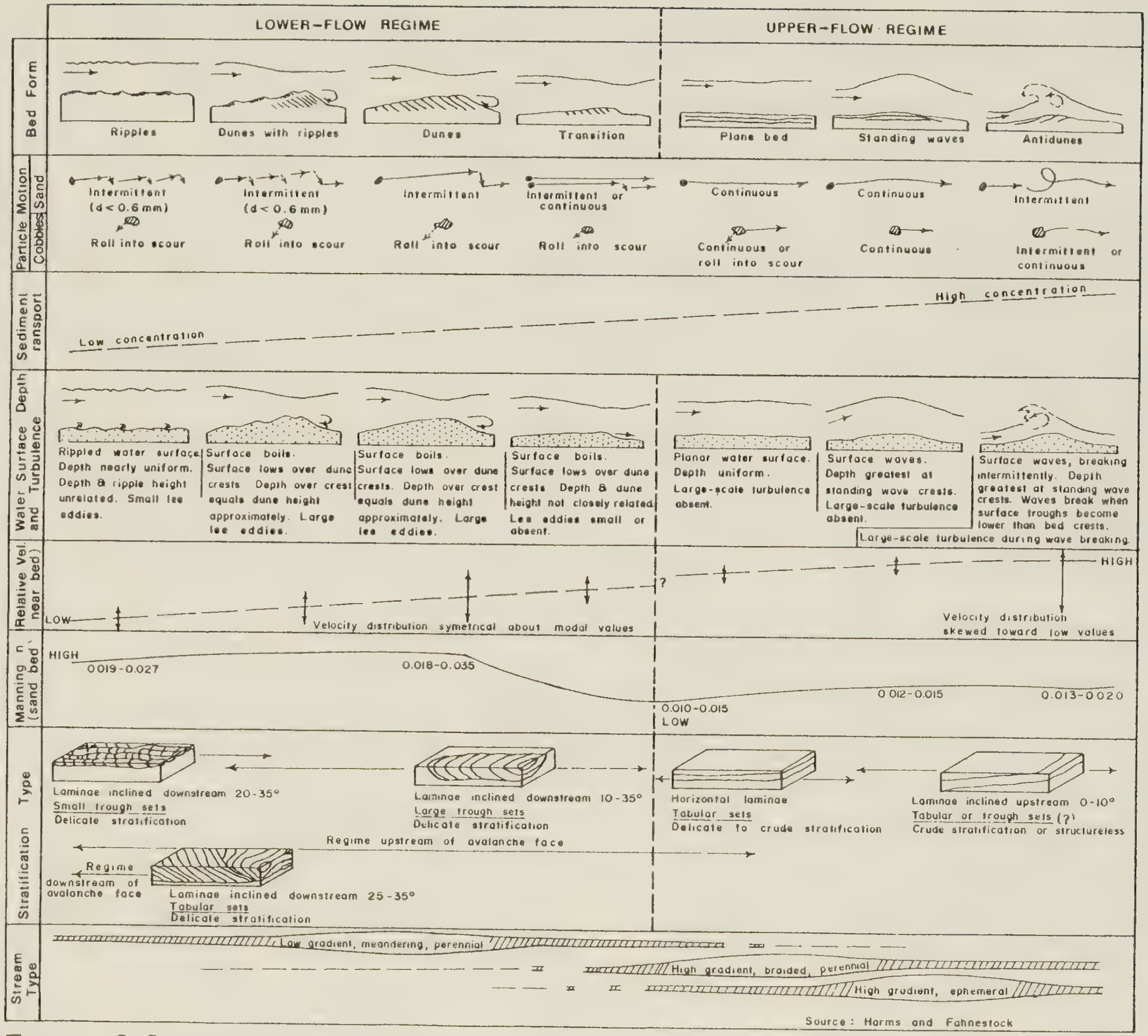


Figure 3-2 Flow regime diagram for sand beds.

These factors are important in assessing flow direction of currents in Glacial Lake Penticton. The methodology and applications of paleocurrent analysis follow those given for cross-bedding and ripple marks by Potter and Pettijohn (1963). They present a description of classification of both cross-bedding and ripple marks and the methods of measurement. The numerous studies and mapping of cross-bedding and ripple marks in different depositional environments indicate preferred rather than random orientation, and reflect the paleoslope.

In the field, the current structures were measured following the technique outlined by Shaw (1975). The directions were recorded measuring the cross-bed dip direction at 90° to the strike of the laminae where the laminae traces are straight in a plane parallel to the bedding. Paleocurrent estimates are plotted individually in figures 4-10 to 4-11 inclusive. Finally, the estimates are combined in a circular frequency diagram fig. 4-18 showing the most probable current direction at the time of deposition for each section and the regional interrelationship.

3.7 Varve Correlation

Regional correlations of varve sequences were first attempted by De Geer (1912), and later adopted by Antevs (1925). The technique involves obtaining measures of varve thicknesses from different sections plotting these

thicknesses on an ordinal time-scale, and visually matching the curves. This method works well over limited distances and within the same depositional basin (provided a marker bed common to each pair of logged sites is found), but correlation between different basins was not considered feasible. However, with the advent of computer programmed statistical techniques, apparently more reliable lateral correlations can be made. Anderson and Kirkland (1966) used a statistical program to determine lateral correlations between stratigraphical non-glacial varves in four sedimentary basins. Their results showed high correlation coefficients (+ 0.80) for laminae thicknesses over considerable distances.

However, late-Pleistocene ice-marginal lakes in mountain regions received large accumulations of sediment during the melt season and deposition during the melt season varied enormously. Therefore, glacial lake varves would show varying thicknesses in response to the topical ice front, mode of deposition and lake development. Large units deposited proximally and found lower in the sections widen the correlation of varve curves when matched against the thin upper units deposited distally and by smaller currents. The rapid development and deposition of sediment in ice-marginal sites would, over time and space, produce curves that would be harder to correlate using Anderson and Kirkland's program.

As previously indicated, the varve-correlation program initiated by Anderson and Kirkland, and as modified by

Higgins (Appendix I) Department of Geography, University of Alberta, was used here. The program correlates thicknesses of a sequence of 'n' varves of one section, with any 'n' varves sequence of another section. "N" can take on the values from five to the maximum number of varves in (the smaller section) each section. For each pair of matched sequences, the correlation coefficient R^2 is calculated along with standard correlation F statistic. An F-test was employed to decide on the most statistically significant match. The use of the highest R^2 alone for the best-match is highly vulnerable, smaller samples can be expected by chance to produce relatively higher R^2 values. This is seen in the trends of a F-table where smaller samples require a higher critical F for rejection of the null hypothesis at a given significance level. The R^2 value, critical F-value and level of significance (Blalock, 1970) were compiled (Table 4-2), and the 'best-fit' varve curves, following the statistical results, between sections were constructed using the method outlined by Antevs (1925, p. 120).

CHAPTER IV

FINDINGS

4.1 Introduction

This chapter describes the seven measured sections, examines their facies states, grain-size distribution, and evidence of paleocurrents directions, and analysis of the patterns of varve correlation. The methodology used, and the results obtained, are presented together with a discussion leading to environmental interpretations of the depositional processes responsible for the fine-grained glacio-lacustrine sediments.

4.2 Stratigraphic Sections

Of the seven stratigraphic sections, three (north Naramata, Naramata, and east Penticton) are found on the east side of Okanagan Lake and four (north Summerland, Summerland, south Summerland, and west Penticton) on the west side (Fig. 1-4). With the exception of east Penticton, the sections represent the best of the exposures allowing reasonable access and measurement. East Penticton has a dangerous cliff below the start of the log, and is only recorded vertically from this point. North Naramata, Summerland and south Summerland exposures are the result of slumping. The logs from each section are numbered according to the number of varve units, from the smallest to the largest.

4.2.1 South Summerland (Log 1)

This section, a road-cut exposure, is 16.5 m high and occurs 8.0 km south of Summerland (fig. 1-4). It is heavily faulted, and subject to frequent slumping (fig. 4-2). The presence of faults throughout the section required that logging of the section begin at a higher point above the base of the section than was anticipated. This section contains only 52 varved units, the smallest number measured.

4.2.2 West Penticton (Log 2)

The second log occurs 3.2 km north of Penticton at Mt. Chapaka Lodge (fig. 1-4) This section is 33.0 m high; however, the uppermost portion of the section has been eroded (fig. 4-3). There are 55 varved units in this section.

4.2.3 North Naramata (Log 3)

North Naramata section is 18.0 m high (fig. 4-5), and lies approximately 8.0 km north of Naramata (fig. 1-4). This exposure, adjacent to the lake, is the result of a massive slump. Below the base of the recorded section is 25 m of silt. This section contains 59 varved units.

4.2.4 Naramata (Log 4)

This section is 36.0 m high and lies adjacent to the lake 0.5 km north of Naramata (fig. 4-4). To measure this section adequately it was necessary to log laterally, as well

FIG. 4-1 Summerland section, log 6. This exposure exhibits recent active slumping resulting from excessive irrigation. The photograph was taken south of the section on the road that traverses this slump. The height of this exposure is 33.0 m.

FIG. 4-2 South Summerland section, log 1. This is the shortest section. The face at the lower left hand corner of the photo is heavily faulted. The material in the foreground exhibits a former slump. The total height of this section is 16.5 m.

FIG. 4-3 West Penticton section, log 2. The top of this section has suffered significant erosion. The 'white-silts' end here at the start of the Penticton flood-plain. Face of this section is 33.0 m high.

FIG. 4-4 Naramata section, log 4. A heavily faulted section with steeply dipping beds towards the south. The photograph is taken half-way up the section looking south. The face of this section is 36.0 m high.

FIG. 4-5 North Naramata section, log 3. The foreground of the photograph is a revegetated large slump that produced this good exposure. The sediment below the rhythmic couplets is composed of contorted and brecciated rhythmic units. The height of this face is 18.0 m.

FIG. 4-6

East Penticton section, log 5. The photograph was taken at the start of the section. Below the photograph is a sheer cliff approximately 20 m above Okanagan Lake. The height of this face is 24.0 m.

as vertically. This section is heavily faulted at its northern end (left side of fig. 4-4), and beds at the base of the section dip at angles of 40-50 degrees. The lower part of the section contains alternating beds of coarse and fine sediments grading into fine lacustrine sediments. There are 69 varved units present.

4.2.5 East Penticton (Log 5)

The east Penticton section is 24.0 m high (fig. 4-6), and is situated 4.8 km north of Penticton (fig. 1-4). However, because of the steepness of the exposure, the log only records the top-half of the section containing fine-grained sediments. It is well exposed, with little erosion, and contains 74 varved units.

4.2.6 Summerland (Log 6)

This section is 33.0 m high and is situated 3.2 km south of Summerland (fig. 4-1). The lower part of the section is masked by a large slump (fig.4-1), composed of fine-grained sediments. No coarse-grained sediments are recorded at this section. There are 78 varves recorded in this section.

4.2.7 North Summerland (Log 7)

The north Summerland section is the highest and best exposed section within the study area. The log is 47.0 m high, extending from lake level to the top of the section

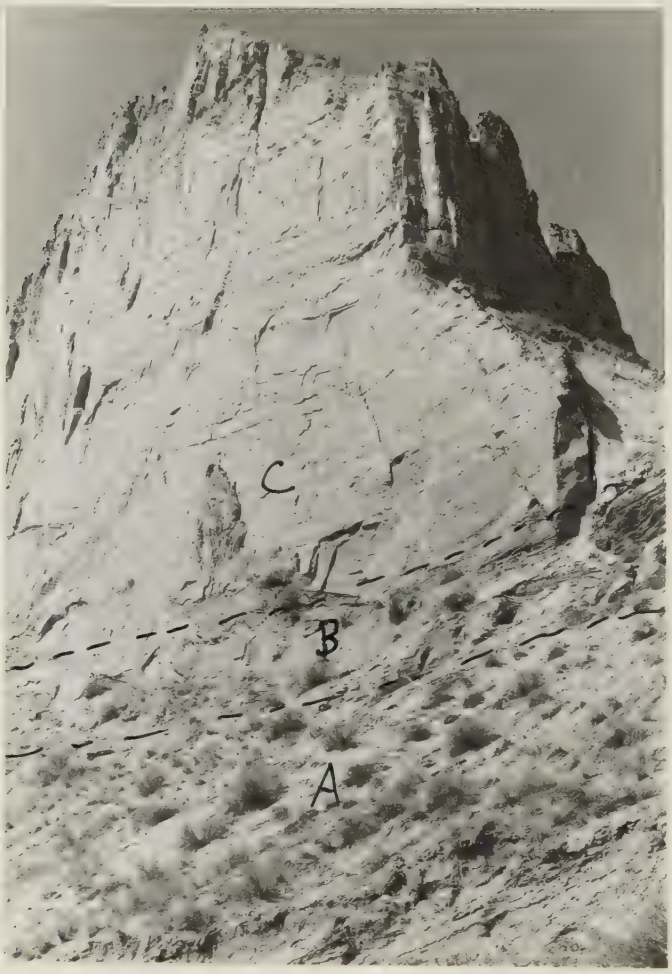


FIG. 4-7

North Summerland section, log 7. The highest and best exposed section in the study area. The photograph was taken from the road about 2 m above the lake. The photo illustrates the lower coarse sediment zone A; the transition zone B; and varved couplets C. The total height of this section is 47 m.

(fig. 4-7), and is located 3.2 km north of Summerland. The lower part of the log contains a large number of coarse (mainly sand) beds, with little faulting or erosion. There are 84 varved units in this section.

4.3 Facies States

Five facies states have been classified to aid in interpretation of the depositional processes and flow regime environments of these sediments. With the exception of gravel and diamicton facies, these facies states are adopted from those outlined by Shaw (1975), and determined by Allen (1970). The facies, shown in Figure 4-8, are:

1. State A-Cross-laminated Sand Facies
2. State A_1-Cross-bedded Sand Facies
3. A_2-Flat-bedded Sand Facies
4. B-Alternating Beds Facies
5. C-Parallel-laminated Facies

4.3.1 Cross-laminated Sand Facies (A)

This facies is well represented in all but two sections - Naramata and south Summerland. The nomenclature of the cross-lamination follows that outlined by Jopling and Walker (1968). However, the type C cross-lamination was not found in the sections. Type A cross-lamination was subdivided following Allen (1968) into tabular or trough units. The Angles of climb were recorded. These units showed low

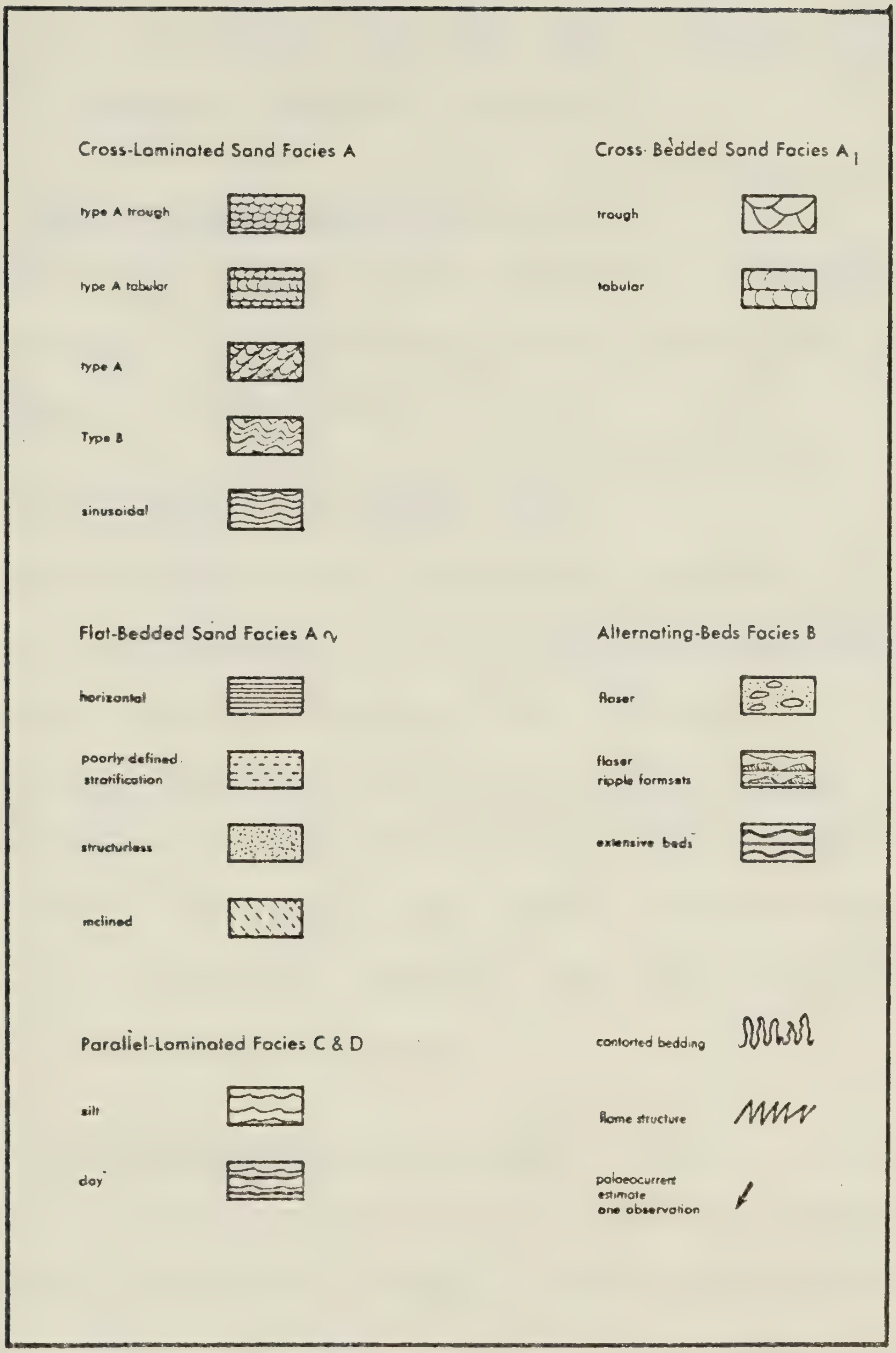


Figure 4-8 Facies states

(for type A) to high (type B) angles of climb and grain size was of a finer texture than facies A_2. This facies occurs both in association with the flat-bedded sands and with the parallel-laminated sediments.

4.3.2 Cross-bedded Sand Facies (A_1)

This facies only occurs in unit 15 of the west Penticton section. The cross-bedded sand facies occurs in association with facies A_2.

4.3.3 Flat-bedded Sand Facies (A_2)

This facies is well represented in five of the seven sections; exceptions are south Summerland and Summerland. The bulk of the lower units in the sections are composed of horizontal and inclined stratified sand beds, with structureless beds showing faint horizontal laminations (fig. 4-8). These units are usually coarse to medium-grained in texture and underlie the cross-laminated facies in vertical sequences.

4.3.4 Alternating-Bed Facies (B)

As with cross-bedded sand facies, the alternating bed facies occurs very rarely. This facies state is most commonly associated with facies C. Occurrence of sets of this facies are found overlying the upper parts of the logs containing cross-laminated sand facies, and underlying the parallel-laminated deposits.

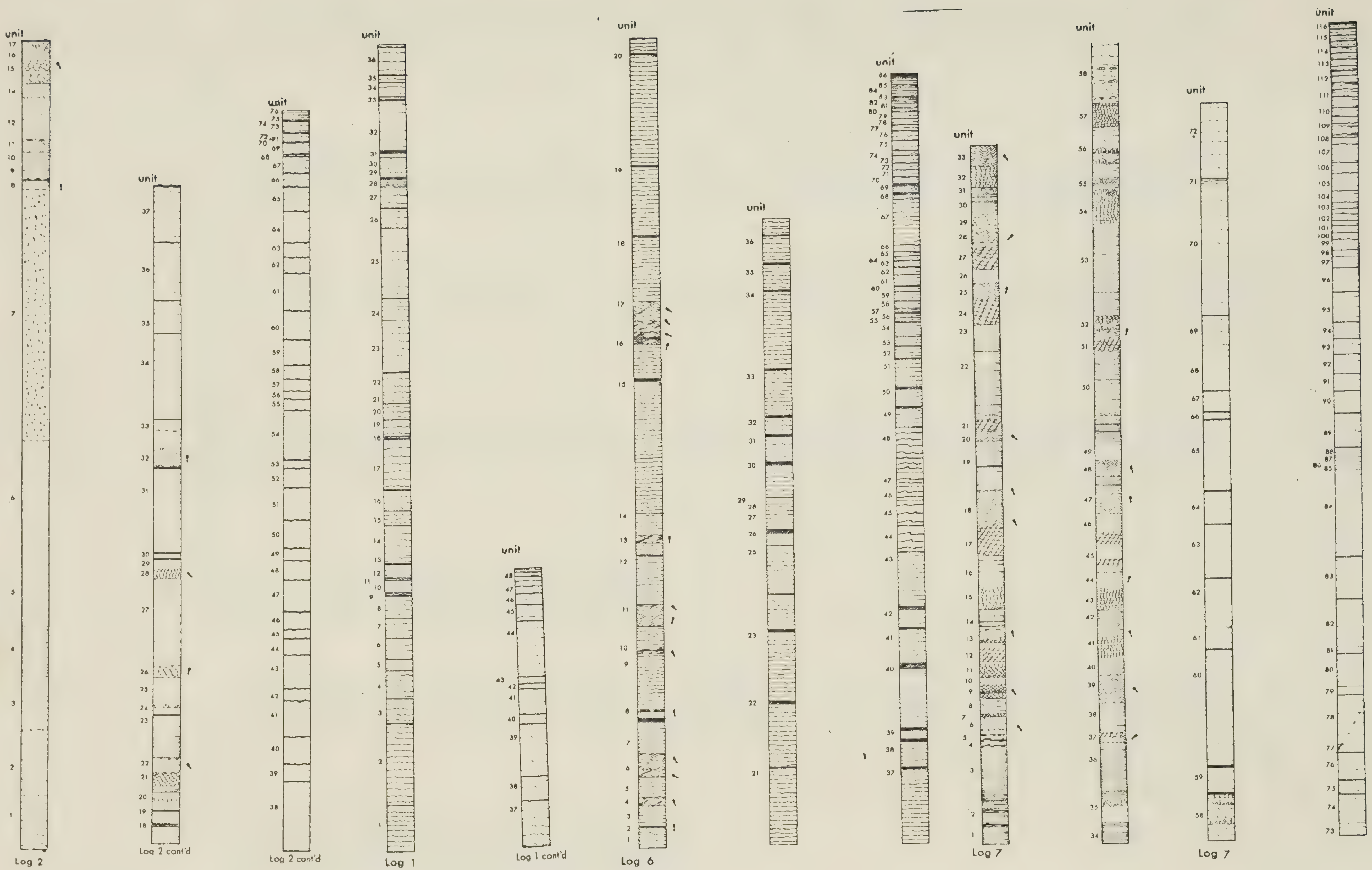


Figure 4 – 9. Sedimentary logs (west sections)

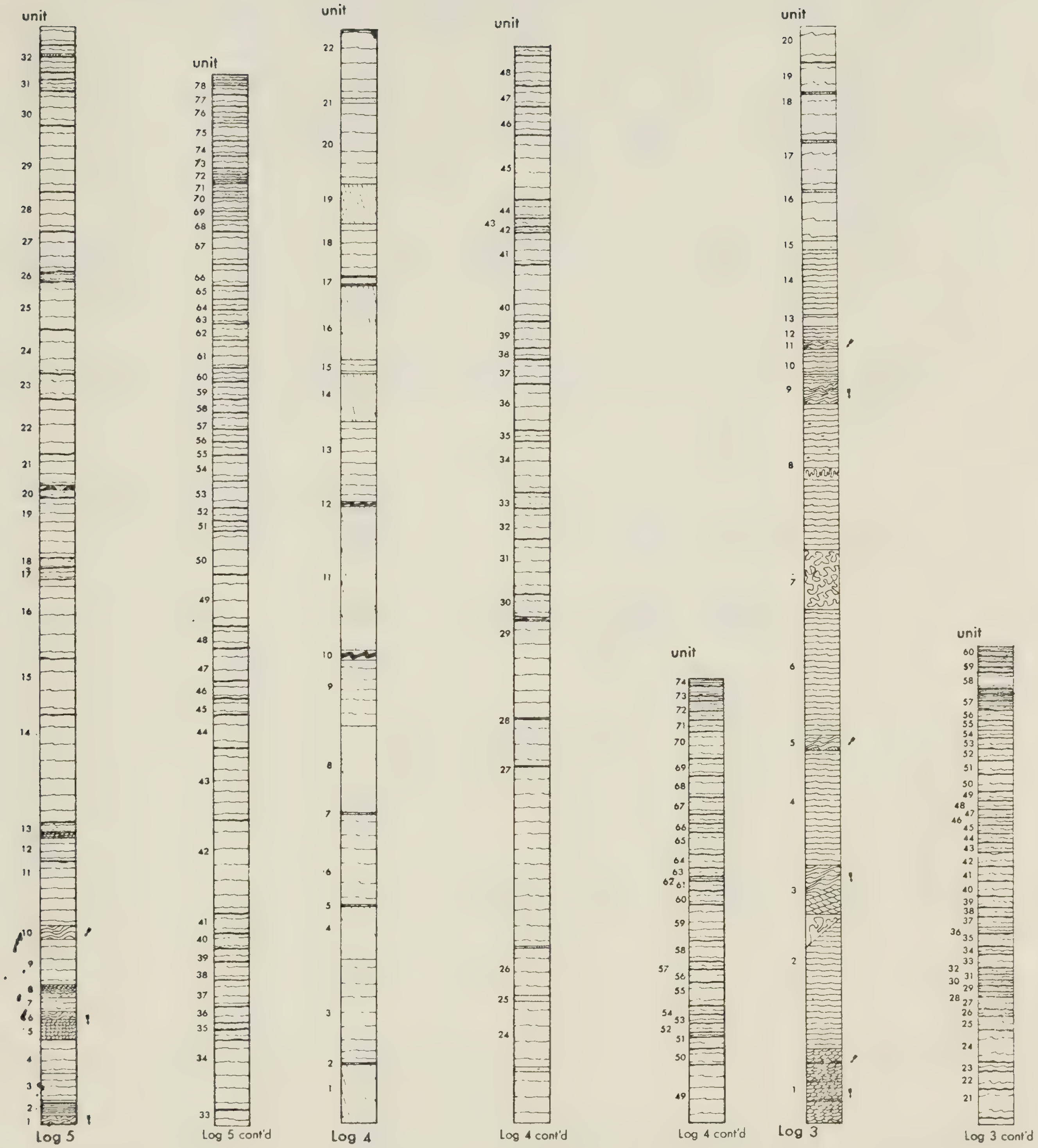


Figure 4-10 Sedimentary logs (east sections)

4.3.5 Parallel-laminated Facies (C) and (D)

This is the most widespread of the facies states (fig. 4-8). These sets have been further sub-divided on the basis of summer (silt) and winter (clay) layers. The silt layers are classified as facies (C) and the winter (D).

In vertical section the laminations may be straight or wavy, and are invariably developed in either facies. The sedimentary surfaces of these facies are transitional or depositional, and minor faulting occurs within the sections.

4.4 Facies Association

An in-depth description and analysis of the facies occurring in the sections allows further analysis of the depositional processes responsible for their origin. The proportional thickness and transition relationships between facies are presented. Shaw (1975) states that these associations may provide, along with a discussion of sedimentary properties, conclusions on the pertinent sedimentary processes acting in glacial lake environments.

4.4.1 Proportional Thickness

Figure 4-11 presents the contribution, by percentage, of each facies to the total thickness of the seven sections. The sections are dominated by the high proportional thicknesses of facies C, D and A_2. Facies A and B are well represented in all sections, but contribute only small thicknesses.

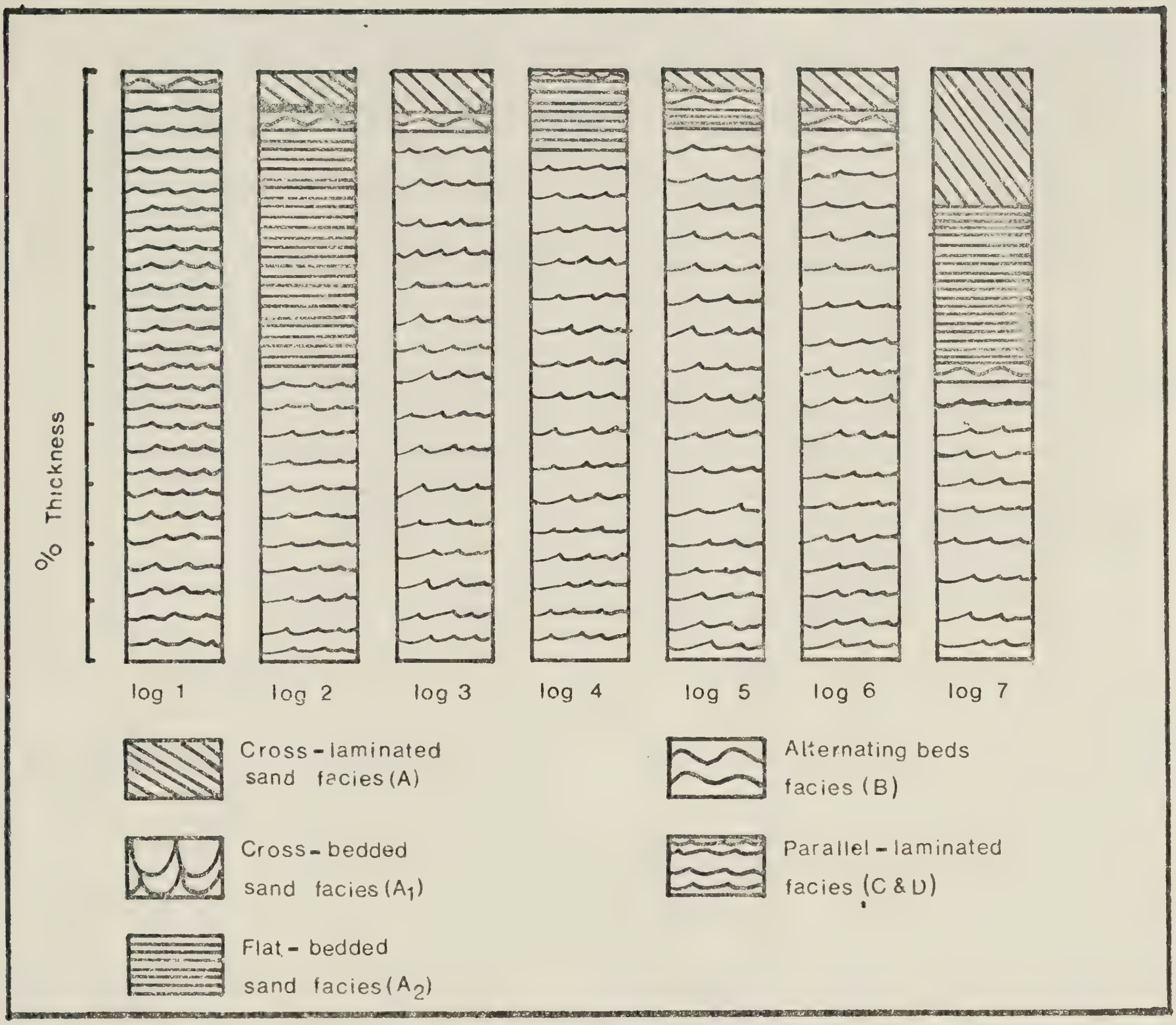


Figure 4-11 Proportional thickness of facies in each section

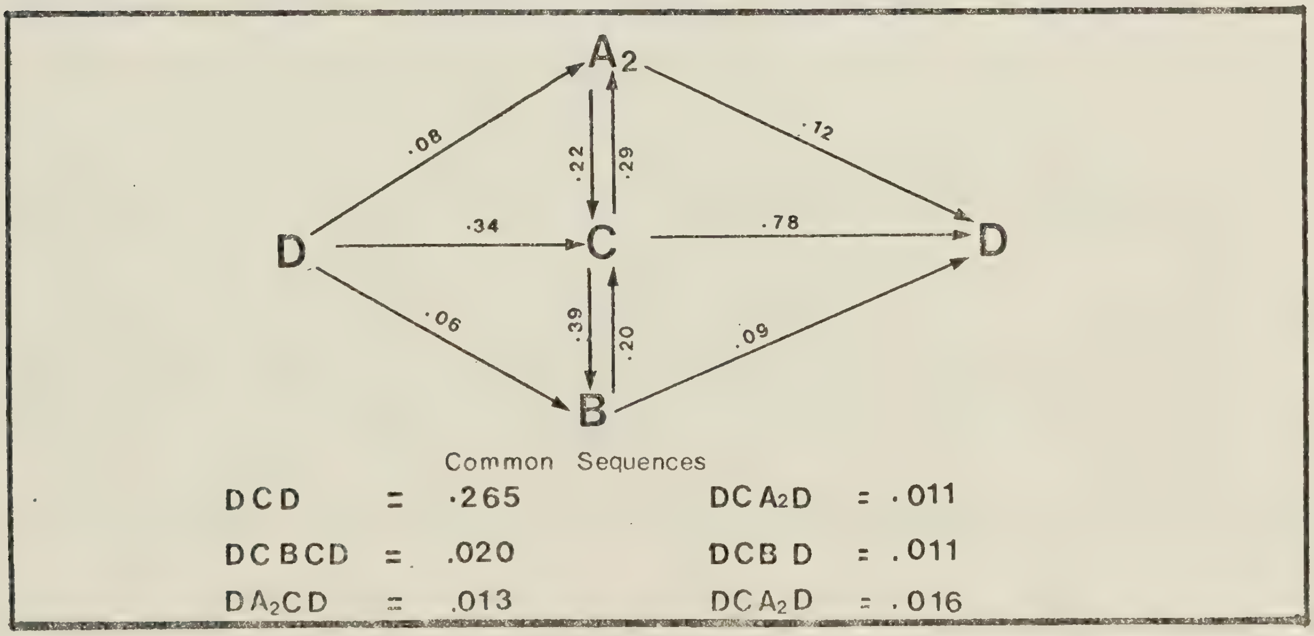


Figure 4-12 Transition tree diagram showing upward facies transitions for selected sections

States A_2, C and D provide an interesting relationship. In logs sampled vertically from the present level of Lake Okanagan, facies A_2 is found in the lower portions. However, these states only occur where nearby streams are found entering the lake, i.e., Trout Creek, and Eneas Creek. The intervening sections fail to exhibit these coarser members in large thicknesses; however, facies states C and D are dominant. The separation of these two facies, whereby C and D overlie facies A_2, is reflected in transition data in Section 4.4.2.

4.4.2 Facies Transition

The transition data for the facies states (except A_1 whose occurrence was minimal) in the six of the seven sections are presented in table 4.1. The transition matrix is the one-step transition method outlined by Krumbein (1967) and applied by Allen (1970a) and Shaw (1975). The upward transition probability, p, is indicated in each box of table 4-1 with each row summing to unity. Figure 4-12 illustrates the important flow branches for the facies states at probabilities of $p \geq 0.10$. The common sequence probabilities are calculated as the product of probabilities for each transition in the sequence (Shaw, 1975). Figure 4-12 illustrates the paths by which state D can be reached after commencing from this state.

TABLE 4-1 - Upward Transition Probability Matrix

Transition \ State	A	A_2	B	C	D	Total
A	-	.57	.14	.27	.02	42
A_2	.43	-	.20	.29	.08	49
B	.22	.32	-	.39	.06	31
C	.23	.22	.20	-	.34	64
D	0	.12	.09	.78	-	32

The transition probabilities in table 4-1 and fig. 4-12 illustrate that the sedimentary succession DCD is the most significant transition. Because of the strong relationship between the summer (silt) and winter (clay) layers it would be expected that this succession is most significant.

4.5 Grain Size Analyses

A thick silt unit was selected at each section and samples, taken at 10 cm intervals, were used in grain size analysis. The following units were sampled: log 1, unit 25-106 cm; log 2, unit 34-104 cm; log 3, unit 13-120 cm; log 4, unit 27-107 cm, log 5, unit 39-104 cm; log 6, unit 45-103 cm; log 7, unit 77-106 cm (fig. 4-9, and 4-10).

It would be valuable to obtain grain size parameters for a time-correlated bed from the sections in a down-valley direction. Unfortunately, time correlation on the basis of statistical methods has not proved reliable, and owing to the intense faulting and discontinuous nature of the exposures it is not possible to "walk-out" a single bed. Alternatively, grain size analysis of samples taken at regular intervals within an individual silt layer allows discussion of the variations in the size of material with time. Common trends in sedimentation can then be obtained by comparison of successions in silt beds at different sites.

As more than 95% of the material passed through the four phi (0.06mm) diameter sieve, size analysis was based on pipette data at one phi intervals. The samples were analyzed to 10 phi. The cumulative percent weight was recorded on cumulative frequency graphs where the ordinate represents the cumulative frequency and the abscissa the phi diameter particle size. From the cumulative frequency graphs, the graphic mean and standard deviation were calculated using Folk and Ward (1957) statistics.

Results for the sections on the east side of Okanagan Lake and those for the west side sections are presented in separate graphs (figures 4-13 A and B). These figures illustrate a scatter plot of standard deviation versus mean grain size for all samples. Of the eastern sections, the North Naramata (log 3) samples are finest ranging from 6.8 - 7.5 ø and the Naramata (log 4) samples the coarsest, ranging from 5.5 to 6.2 ø. The mean grain size values for samples from East Penticton (log 5) lie between the North Naramata and Naramata samples, from 6 - 7 ø. Generally, standard deviation values range from 1.3 to 1.9 ø, with the majority of samples found between 1.4 and 1.6 ø.

North Naramata (log 3) samples exhibit high mean ø values indicating finer grain size of silt with very little inclusion of coarse size fractions. Moreover, as indicated by standard deviation, the samples show poor sorting. The Naramata section (log 4) downvalley exhibits coarser grained deposits shown by the lower mean ø values. Sorting of the samples, however, shows a fairly uniform distribution. The East Penticton (log 5) samples exhibit a wider range of grain size from coarse to fine silt. Furthermore, the standard deviation values indicate well sorted for some of the samples and poor sorting for the finer samples.

Samples from the west sections do not fall into the distinct clustering exhibited by samples from log 3 and 4 of the eastern sections. Overall the mean grain size values for most of the samples range from 6 - 7 ø with only a small

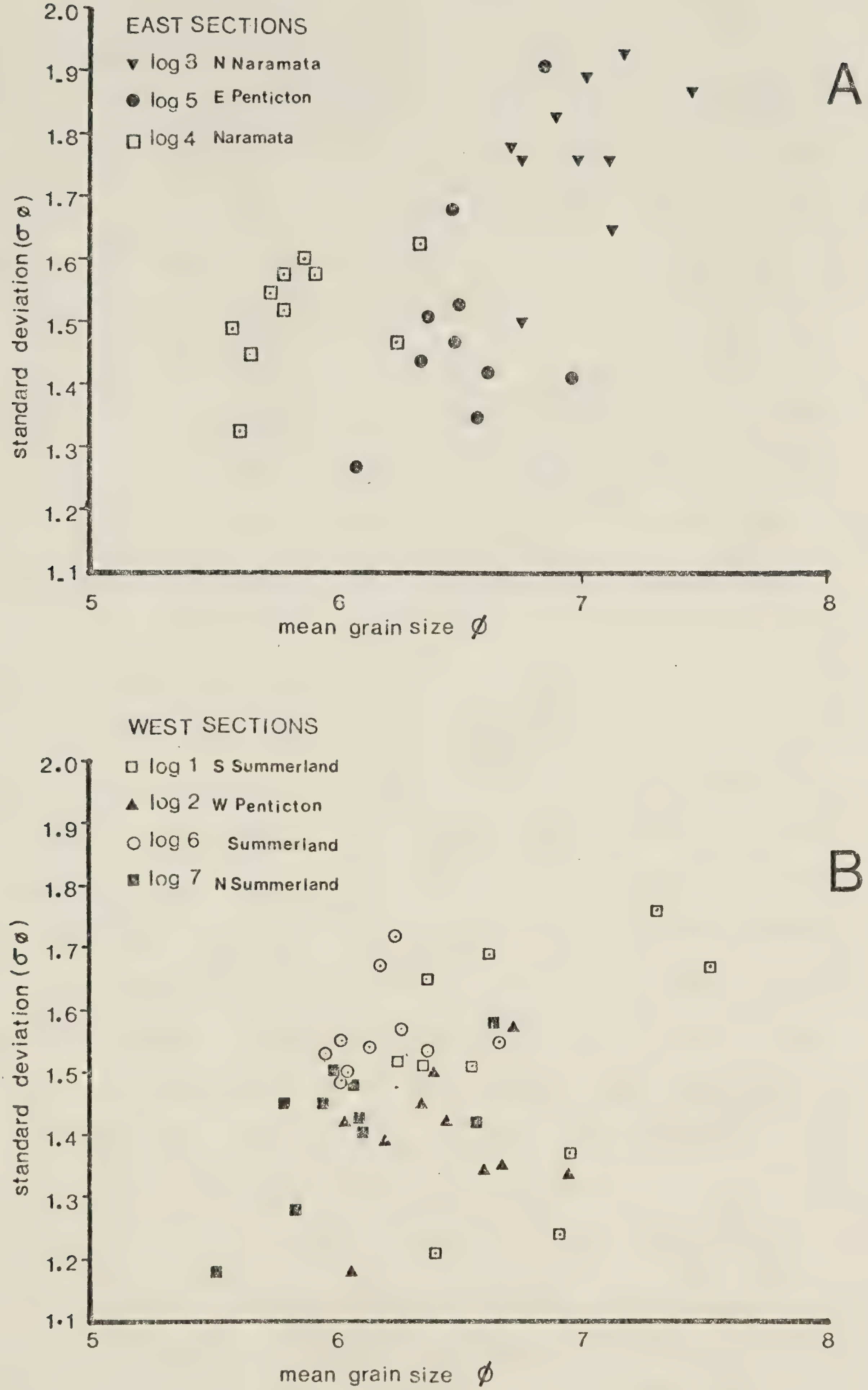


Figure 4-13. Scatter plot mean grain vs standard deviation

number of samples coarser than 6 ø or finer than 7 ø. Standard deviation values generally range between 1.4 and 1.6 ø, although samples from three of the sections are found below 1.4 ø. North Summerland (log 7) exhibits the coarsest and best-sorted sample at 5.5 ø and 1.3 ø with the majority of the other samples found between 5.8 to 6.5 ø and 1.4 to 1.6 ø. The nearest section, Summerland (log 6), downvalley shows finer grained samples clustered from 6 to 6.8 ø. These samples also show a narrow range of standard deviation values - 1.5 to 1.7 ø. The South Summerland (log 1) samples are widely divergent with mean grain size values ranging from 6.2 to 7.5 ø. Sorting is also variable ranging from 1.2 to 1.8 ø. Samples from West Penticton (log 2) are similar in mean grain size and standard deviation to East Penticton (log 5) samples. A single sample is coarser and well sorted with the majority of the samples in the unit being finer and less well-sorted.

Generally, the samples from the eastern sections (North Naramata and East Penticton) are finer and less well-sorted than those of the western sections. The western side of the Okanagan has larger tributaries (fig. 1-3) and coarser fractions may have been supplied to this part of the proglacial lake. Nevertheless, the Okanagan samples collectively correspond in mean grain size vs standard deviation to silt layer grain size values found by Ashley (1975) and Banerjee (1973) (fig. 4-16). Ashley found that mean grain size in silt layers varies according to the environment of deposition. Her varve group III classification (clay thickness less than silt thickness) is similar to the couplets found in the

Okanagan. In addition, Ashley found that the silt layer was composed of laminations of varying grain size, and does not always fine upwards. The detailed grain size distribution diagrams (figs. 4-14 and 4-15) of the Okanagan samples reflect similar depositional characteristics. Ashley states that the genesis of group III varves are thought to be associated with the formation of lacustrine deltas by density underflows.

Banerjee (1973) also showed that silt layer grain size distribution varies according to the mode of deposition. He concluded that coarse and better sorted silt layers with cross-lamination originate from turbidity currents with bed-load transport. Conversely, the silt layer of varves with a size range of 5 ø to 8 ø, without cross-lamination, are thought by Banerjee to be the result of turbidity currents without bedload. The Okanagan samples generally fall within the size distribution outlined for silt deposited by turbidity currents without bedload (fig. 4-16).

Comparing this study to the ones mentioned above, the sections present grain size characteristics that suggest specific depositional processes. The North Naramata (log 3) unit (fig 4.14) shows a general decrease in grain size up to 60 cm above the base. The upward fining of the silt is mirrored by a decrease in sorting. The 70 cm sample shows an increase in mean grain size while sorting decreases. From 70 cm above the base until the onset of the winter (clay)

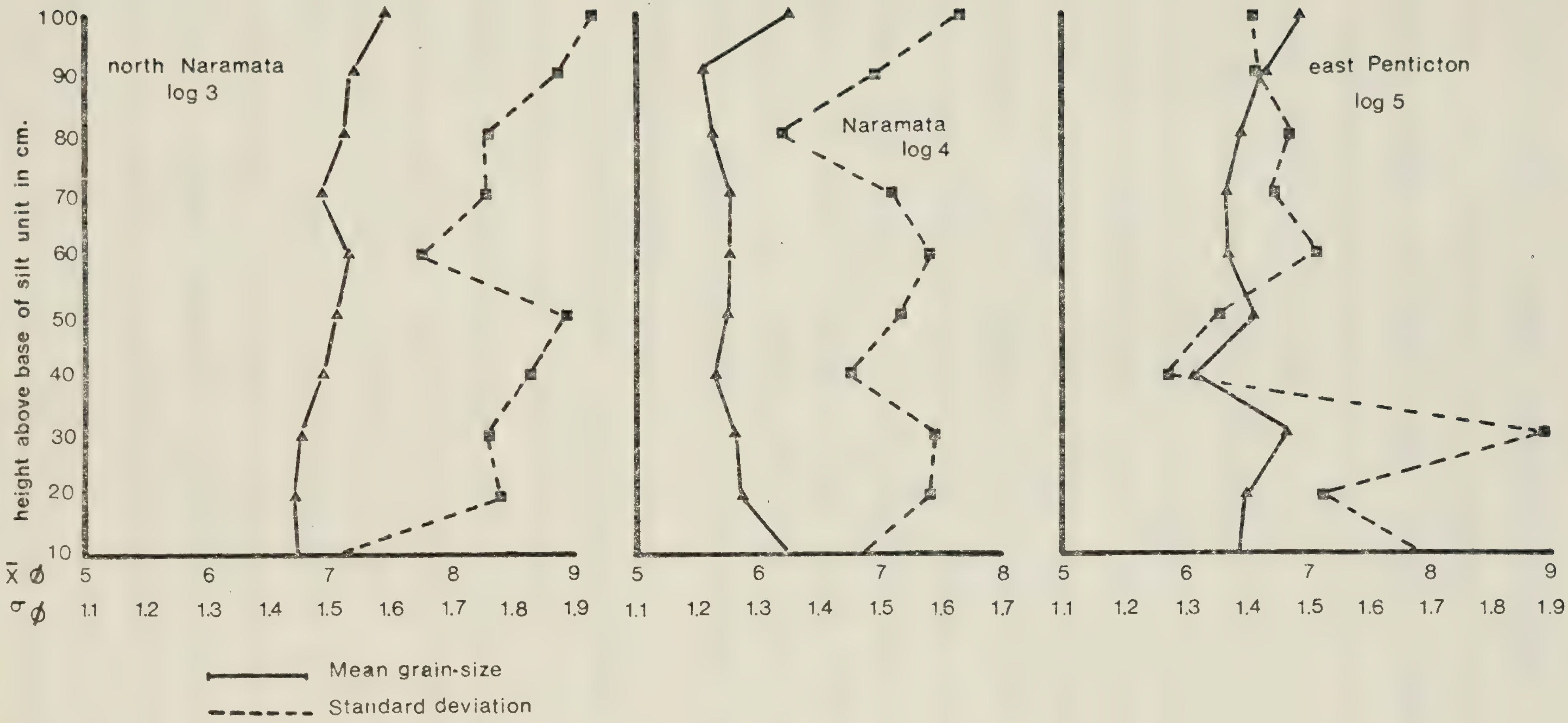


Figure 4-14 Grain-size analysis of samples taken at regular intervals for east Okanagan sections

layer the samples become progressively finer and more poorly sorted. The increase in grain size at 70 cm could possibly indicate deposition from a more powerful underflow event. The remainder of the samples seem to indicate deposition from low velocity currents.

The Naramata (log 4) unit appears to be the opposite of the North Naramata section. The mean grain size increases until 40 cm above the base of the unit. Although the higher deposits are coarser, the sorting does not improve until 40 cm sample. From samples 40 to 70 cm there is a slight fining trend with poorer sorting. The mean grain size increases from 70 to 90 cm with an improvement in sorting at 80 cm. The last two samples show rapid fining prior to the winter layer. This section has two samples (40 and 80 cm) in which coarser and better sorted silt was deposited from stronger currents.

The East Penticton (log 5) unit samples show a more varied change in grain size with height. The mean grain size decreases to 30 cm above the base. The sorting improves from the base of the unit to 20 cm, but then decreases at 30 cm in conjunction with the increase in fines. The 40 cm sample exhibits an increase in coarse material with significantly improved sorting. The sample at 50 cm is finer, although there is only a slight decrease in sorting. From 50 to 70 cm a slight increase in mean grain size occurs with poorer sorting. The final four samples show a slow fining trend toward the winter layer, but rather than sorting becoming poorer, the

90 and 100 cm samples show improved sorting. This is somewhat of an anomaly in comparison with the other two sections where sorting is poorest at the 100cm sample. This unit can be interpreted as follows: the 30 cm sample may indicate deposition from a turbulent suspension with fine poorly-sorted material. The 40 cm sample may be the result of a higher velocity current that transported coarser better-sorted material in response to higher melt-water inflow. Above 40 cm lower velocity currents depositing finer and less well sorted material seem likely.

The west sections (fig 4-15) show a more varied change in grain size distribution. The North Summerland (log 7) unit exhibits an increase in mean grain size up to the 30 cm sample. Sorting is poorer at the 20 cm sample but rapidly improves with the coarser material at 30 cm. From 30 cm to 70 cm the silt is alternately finer then coarser. The sorting is poor and does not fluctuate in response to the fining and coarsing. The 80 cm sample shows a rapid increase in mean grain size with improved sorting. The final two samples fine rapidly upward with a decrease in sorting. This unit exhibits an alternating decrease and increase in fining that may be a response to more variable current velocities. The coarse and better sorted samples at 30 cm and 80 cm suggest underflow events; whereas, the remainder of the samples may be indicative of lower velocity pulsating currents carrying finer and poorly sorted material.

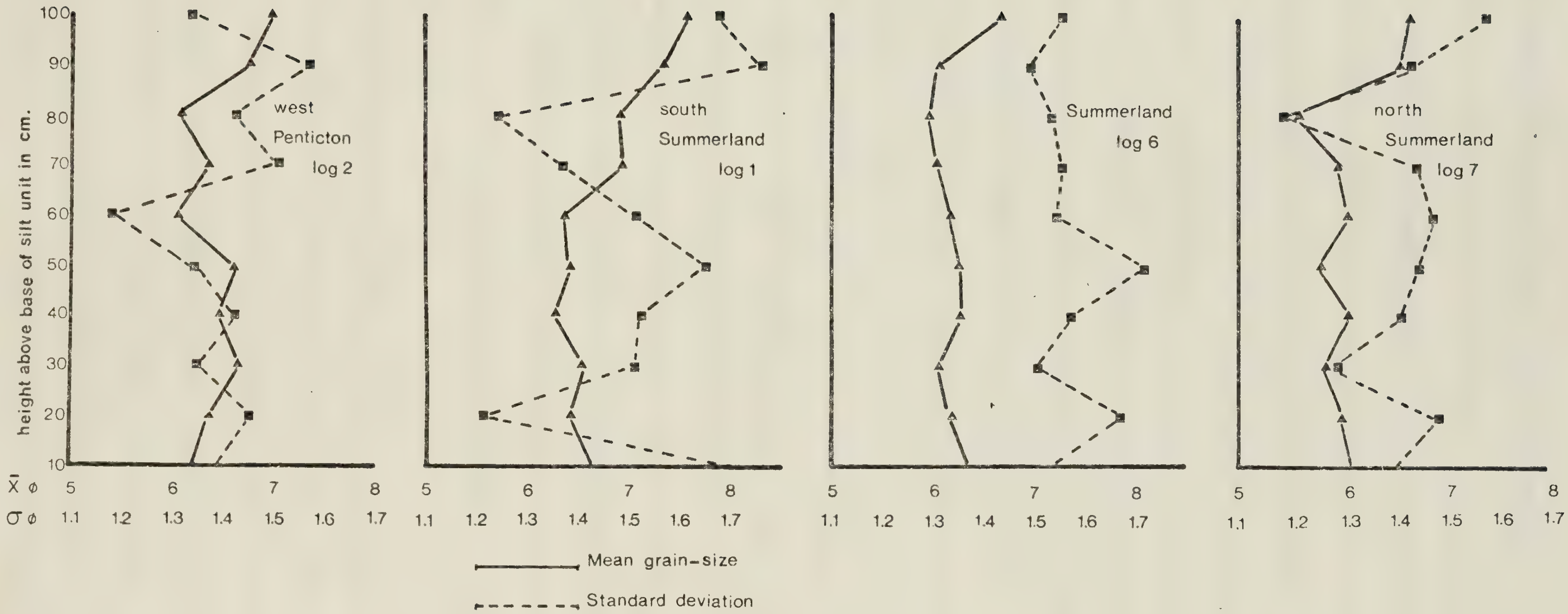


Figure 4-15 Grain-size analysis of samples taken at regular intervals in west Okanagan sections

The Summerland section (log 6) shows an increase in mean grain size to the 30 cm sample. The sorting is poorer at 20 cm and then improves at 30 cm. From 30 - 40 cm there is a decrease in grain size and sorting is poor. The grain size coarsens gradually from 40 to 80 cm with sorting poor. The final sample is fine and shows poor sorting. This unit does not show a varied change in grain size as does the up-valley section (log 7). The grain size profile is similar to the North Naramata and Naramata sections where low velocity currents deposited finer poorly-sorted silt. The sample at 30 cm is the only one which exhibits relatively good sorting and coarse grain size.

The South Summerland (log 1) unit shows a similar mean grain size trend to North Summerland. There is an increase in mean grain size from the base of the unit until 20 cm with improved sorting. From 20 cm to 60 cm the sediment is alternately finer and coarser with decreased sorting. Finally, there is a gradual fining trend from 60 cm to the top of the unit. There is an improvement in sorting at 80 cm but the top samples show poor sorting.

The West Penticton (log 2) unit exhibits a fining trend from the base of the unit to 30 cm. This is similar to the East Penticton section unit. The sorting is poor from the base to the 20 cm sample, but improves at the 30 cm sample. Samples from 30 to 80 cm are alternately coarse and fine, with a rapid fining trend from 80 to 100 cm. Sorting is poor from 30 to 60 cm where the silt is coarsest. From

60 to 90 cm the sorting is poorer, but then rapidly improves at 100 cm corresponding to the East Penticton section.

Generally, the North Summerland, South Summerland, East and West Penticton sections show stronger alternate coarsening and fining trends within the profiles. Also, one or two samples exhibit relatively coarse grain size and good sorting either at 20 to 30 cm and 60, 70, or 80 cm levels. North Naramata, Naramata, and Summerland units show only slight fining and coarsening trends with generally poor sorting. Nevertheless, each unit does show one sample that is coarser and better sorted either at the 30, 40, 60 or 80 cm above the base. In all sections the mean grain size rapidly decreases from 80 to 100 cm samples. Moreover, except for East and West Penticton, the degree of sorting is poorer in conjuction with this fining trend.

The units are not graded such that mean grain size increases from the base to the top, as would be expected in turbidite or single current deposition. Rather, the samples suggest that a series of currents were responsible for the genesis of the silt units. Individual currents in response to meltwater inflow deposited the silt throughout the melt season. Larger underflow events may be indicated by the increase in mean grain size and lower standard deviation values.

The grain size analysis indicates that samples from the Okanagan were similar in grain size distribution to those observed by Ashley (1975) and Banerjee (1973). Furthermore,

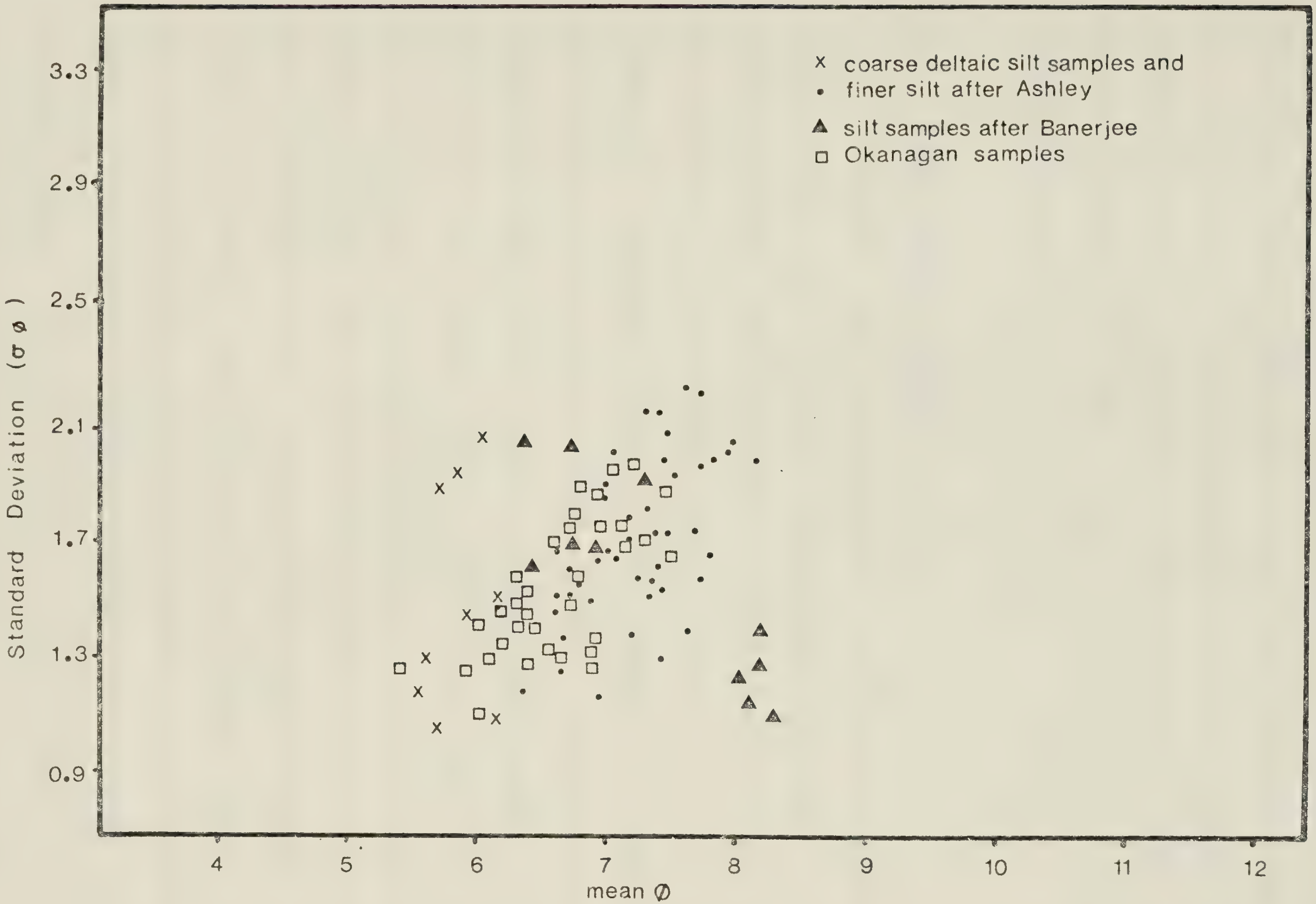


Figure 4-16 Distribution of silt grain-sizes after Ashley (1975) and Banerjee (1973) compared with Okanagan samples

processes of sediment deposition by turbidity currents seem to be the best explanation for the changes in grain size and sorting within large silt units. Individual currents deposited coarser sediment giving rise to lower mean grain ø values and lower standard deviation values. Conversely, currents of lower velocity or from a more distal sediment source may have deposited finer-grained and poorly-sorted sediment.

4.6 Paleocurrent Directions

Paleocurrent estimates obtained from cross-laminae and cross-strata are shown individually in figs. 4-9 and 4-10 inclusive, and combined in figure 4-17. The individual sections show paleocurrent distributions that are distinctly bimodal or trimodal. Allen (1970) states, ..."directions (from turbidite bedding) remain almost constant over very large areas and persist with only slight changes." This observation has given rise to the concept that the basic regional control of paleocurrents was the paleoslope, and a single source. The Okanagan Valley would have acted as a basic regional control where paleocurrent estimates illustrate a north to south trend following the valley slope. However, the bi and tri modality of the combined estimates illustrate that a single source current system is not valid for an ice-marginal lake. Gustavson (1975) clearly showed that turbidity currents originated englacially, super-glacially, and from a delta origin in Malaspina Lake. Depending upon the

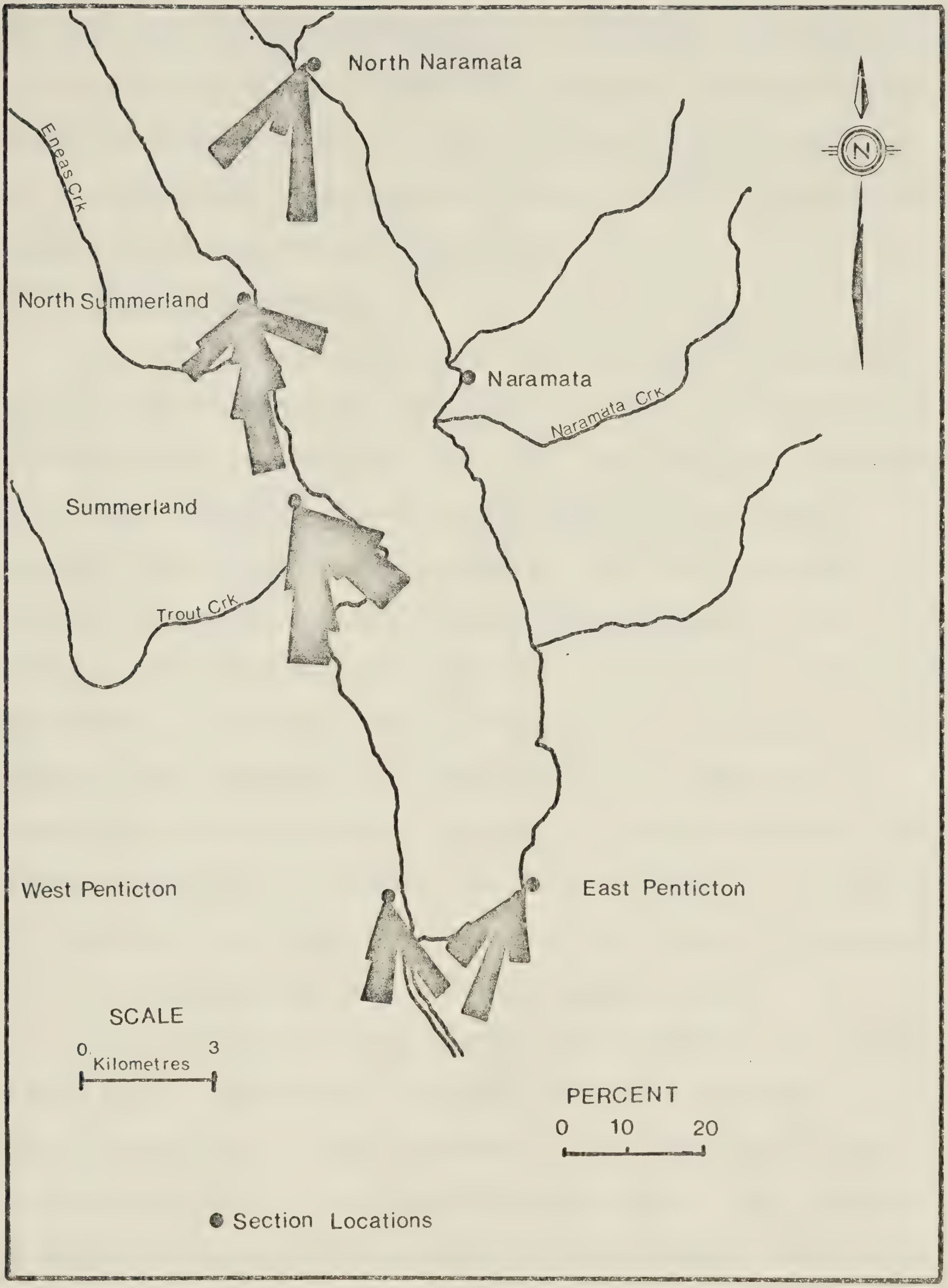


Figure 4-17 Paleocurrent directions

source and fluctuations during the meltseason, paleocurrents originating in glacial lakes from turbidity flows would be expected to be bimodal or polymodal similar to those found in the Okanagan, whereas flow directions from a fixed delta source would show more unimodality.

4.7 Varve Correlation

An attempt was made to derive a best-fit correlation between the varved units for all the sections. The results are presented in Table 4-2 and figs. 4-18 and 4-19 inclusive. The table indicates the units that match between each section, and in all cases almost all the units in each section correlate at .001 level of significance. The figures show evidence that the thick units, at the bottom of the sections, dominate the correlation. In a complete analysis of this technique, it was found to be impossible to accept these correlations. Basically, it seems to fail for the following main reasons: (1) the program is attempting to correlate time dependent units on the basis of thickness, and (2) the program uses pair-wise correlation.

Generally a proximal varve will be thick and a distal varve thin. Therefore, the units were time dependent in their properties. Also, thickness varies systematically within each section and throughout the basin. The program simply correlates the thickness of units between each pair of sections.

Therefore, correlations based on thickness cannot be equated as time dependent units especially when no marker

TABLE 4-2

Varve Correlation

ion Y	R^2	Section X Units		Section Y Units	F:Stat-istic	Level of Significance
2	.4653	1-52	,	1-52	13.8187	.001
3	.6893	1-49	,	11-59	15.3920	.001
4	.5549	9-52	,	1-44	18.6862	.001
5	.4544	1-52	,	10-61	13.0078	.001
6	.4362	1-52	,	19-70	11.7466	.001
7	.5168	1-52	,	26-77	18.2246	.001
3	.7813	1-55		4-58	83.0263	.001
4	.7394	1-55		14-68	63.9240	.001
5	.5760	6-55		1-50	23.8286	.001
6	.7757	1-55		19-73	80.0563	.001
7	.8366	1-55		26-80	123.6233	.001
4	.7953	1-59	,	11-69	98.0893	.001
5	.5418	1-59	,	6-64	23.6875	.001
6	.7733	1-59	,	19-77	84.7852	.001
7	.5962	1-59	,	13-71	31.4378	.001
5	.5605	1-57	,	18-74	25.1960	.001
6	.7403	12-69	,	1-58	67.9097	.001
7	.6394	2-69	,	1-68	45.6478	.001
6	.5661	1-64	,	15-78	29.2441	.001
7	.5848	1-74	,	9-82	37.4220	.001
7	.6027	1-66	,	18-83	36.5017	.001

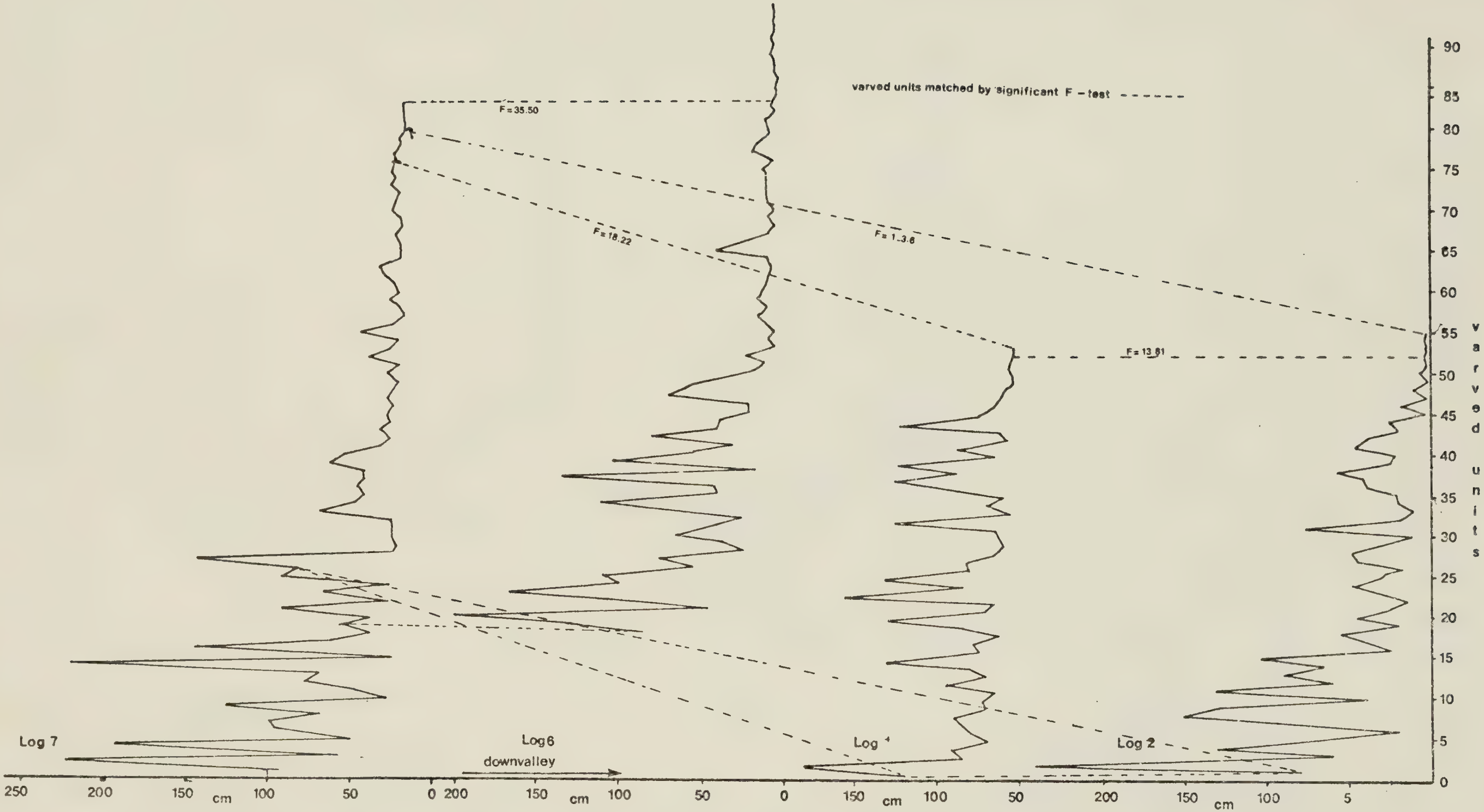


Figure 4-18 Varved units matched for sections on the west side of Okanagan Lake

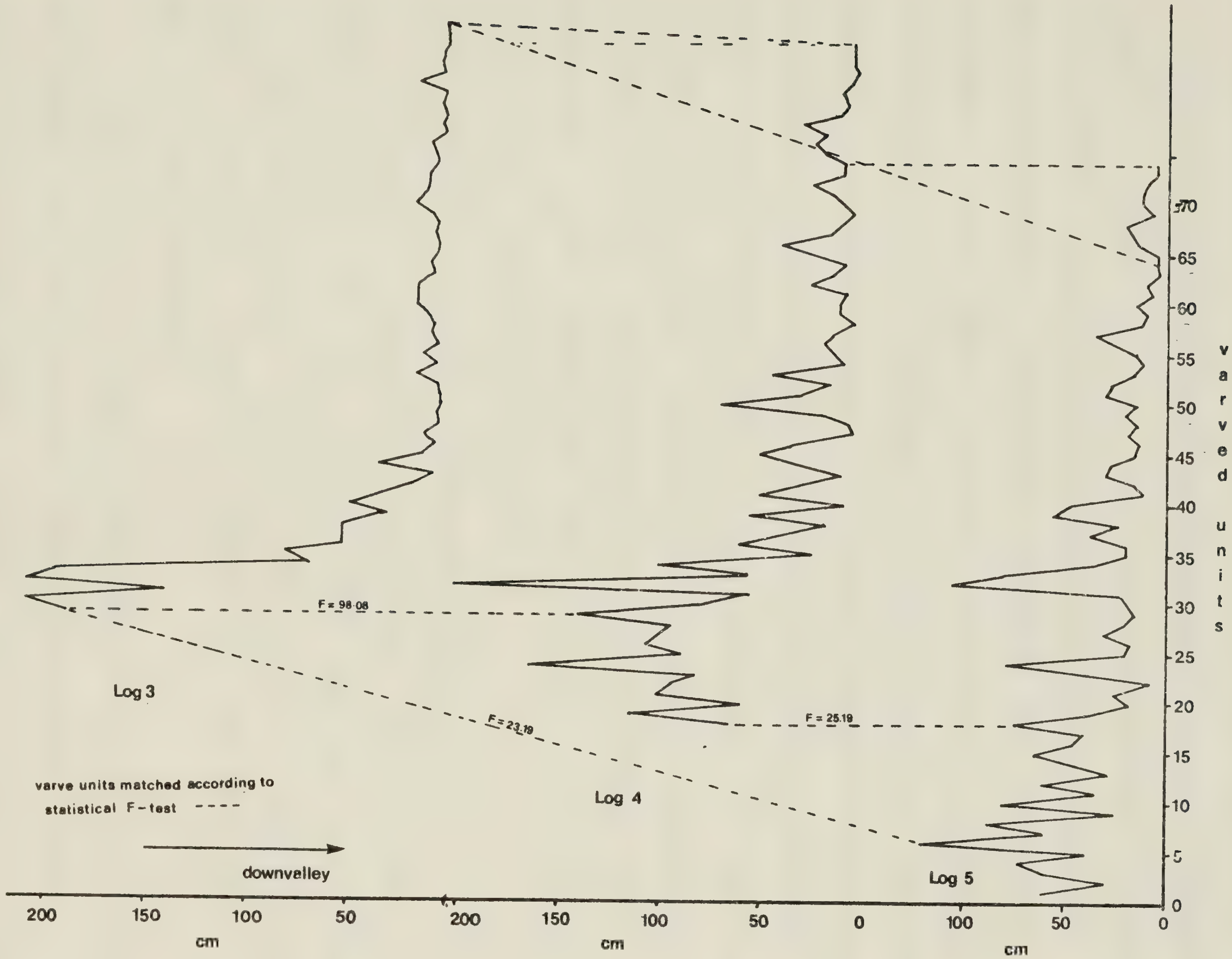


Figure 4-19 Varved units matched for east Okanagan sections

bed is identifiable throughout each section.

Furthermore, the correlation program has a weakness in its construction. This computer program uses pair-wise correlation. Table 4-2 and the following example illustrates a problem inherent in this type of sampling method. Section 1 was matched against section 2 with 1-52 vs 1-52 as the best-fit sequences, and section 2 matched against section 3 indicates 1-55 vs 4-58. However, when section 1 is matched against section 3, 1-52 should be matched against 4-55. As table 4-2 indicates however, section 1 against 3 shows units 1-49 matched against 11-59. The program should have been written to correlate all sections in sequence. In addition, in order to adequately assess all correlations between two 50-unit sequences, approximately 50,000 comparisons would be needed. Such a degree of computation is, for studies of this nature, prohibitively expensive.

4.7.1 Alternate Methods to Correlate Varve Units

Although the results of the program indicate that it does not work, there are, with further research, hopes that it might be applicable to varve correlation in ice-marginal lakes. There are a number of steps that offer some improvement in this technique.

The difficult problem in the field was the identification of a marker bed that could be identified through lateral gradation in all sections. If such a bed is identified from section to section through a computer program, then a time correlated unit can serve as the basis for correlation

attempts. Further research on the Okanagan sediments may reveal such a marker bed, and therefore facilitate the generation of correlated units. The program will have to be re-written to accommodate a section by section analysis. An approach whereby the difference between units is divided by the value of the lower unit and multiplied by a hundred can be considered. Units for sections can be plotted and then matched up against other sections. Identical values in sequence, if found, can be followed vertically to indicate correlated units (Shaw, personal communication). This approach may offer an improved means of establishing current events in ice-marginal glacial lake deposits.

4.8 Discussion

The results allow interpretation of the depositional environment of the lacustrine sediments found bordering the southern end of Okanagan Lake. The depositional environment can be interpreted on the basis of the vertical sequence of the stratification types and flow regime. Also, interpretation is supported by sedimentary structures, paleocurrent and grain size analysis. Furthermore, studies of sedimentation processes active in modern glacial lakes are valuable in reconstructing the complex processes that occurred in ice-marginal and pro-glacial lakes during the Pleistocene.

Within the study area the sediments generally show a coarse to fine vertical gradation. The lower portions of the logs (where recorded) exhibit fine sand or coarse silt

in which stratification types allow deduction of depositional processes. In particular, log 7 offers an excellent record of texture, bedform, and current directions. The alternating coarse and fine sediments, with their stratigraphic position, offer support for deposition in a lake delta or pro-delta environment.

A transition environment is tentatively identified where alternating beds, convolute laminations and load structures of sand and silt overlie the coarser sediments and grade vertically into the fine-grained laminated varved deposits.

The upper zone of the logs are varved sediments. The couplets are massive in size above the coarse deposits, and their texture is coarse silt with thick winter clay layers. Vertically in the sections the couplets become smaller and finer-grained.

Using data compiled in this chapter it is possible to tentatively establish processes occurring at the time of sediment accumulation. Moreover, these allow interpretation and reconstruction of the environments.

CHAPTER V

SEDIMENTARY INTERPRETATION

5.1 Introduction

The sedimentary associations exhibited both vertically and laterally in the seven logged sections offers stratigraphic evidence of depositional processes active in glacial Lake Penticton. These allow interpretation and reconstruction of the environment based on the data collected, their analysis, and other observations of lacustrine sedimentation.

The sections reveal an upward fining gradation through which three sedimentary environments are proposed. The lower sections where logged (log 2, 4, and 7), are composed of coarse-grained proximal deposits deposited in glacio-lacustrine deltas. Two sedimentary successions are recognized: one reveals a simple alternating of flat-bedded sands and coarse silt facies; the other of flat-bedded sands overlain by cross-laminated sands.

A transitional environment (following the model of Jopling and Walker (1968) (fig. 5-1) is proposed between proximal glaciodelta and distal glaciolacustrine facies. Alternating sand structures, load structures, and laminated silts may indicate deposition in deeper water, probably in subaqueous levées.

The third environment proposed is the glaciolacustrine in which fine-grained varved couplets were deposited by turbidity currents and suspension settling in deeper water

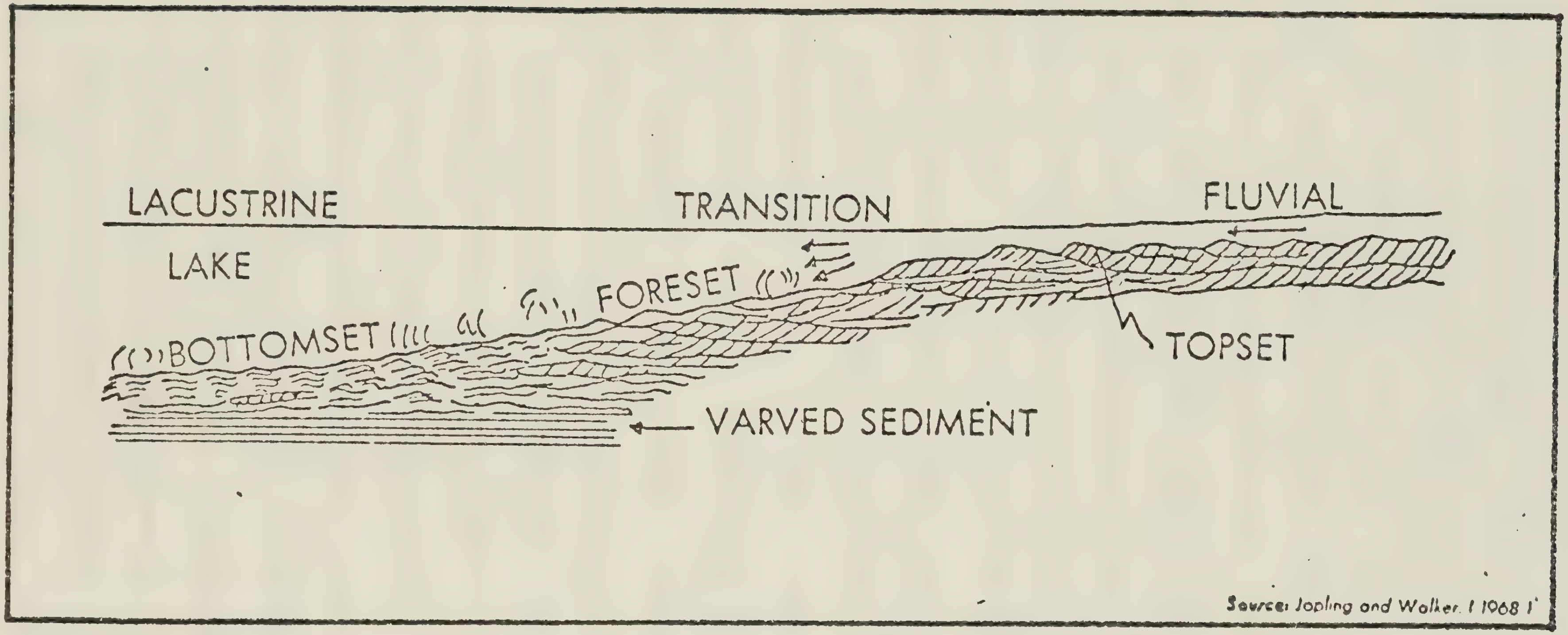


Figure 5-1 Diagrammatic representation of the environmental conditions of deposition in a Kame delta deposit

following retreat of the topical ice front.

5.2 Coarse-Grained Deposits

Two sedimentary successions are recognizable in the lower units of logs 2, 4, and 7 (figs. 4-10 and 4-11). A simple succession of flat-bedded sands (A2) alternating with laminated silt facies (C) occurs in logs 2 and 4. In log 7, flat-bedded sands are overlain by cross-laminated sands in a cyclic upward fining sequence that is slightly more complex.

The flat-bedded, inclined sands are overlain by coarse silts in an alternating sequence in the lower units of logs 2 and 4. The sand units are thick and of medium to fine texture. The silt units are also thick, in comparison to silt units found higher in the sections, and extremely coarse in texture. The sand units have sharp tops and bases, and faulting occurs in both facies. Although these lower units in logs 2 and 4 illustrate a simple succession, the changes in geometry and texture illustrate the processes and environment in which deposition took place.

The flat-bedded sand facies show poorly defined stratification, horizontal, inclined and structureless sand units. The internal geometry and texture of the units indicate deposition under the upper flow regime. Moreover, structureless sand bed forms are considered by Harms and Fahnestock (1965) (fig. 3-2) to be deposited under the upper part of the upper flow regime, commonly in shallow braided streams. Harms and Fahnestock describe plane bedded sands as forming under shallow areas on bars in the fluvial environment. However, in studies on glaciolacustrine deltas,

flat-bedded sands have been interpreted as accumulation of channel deposits. Shaw (1975) presents flat-bedded sands found in lower stratigraphic positions of glaciolacustrine deltas as multi-storied channel deposits. Further support for these units as distributary channel deposits comes from Gustavson, Ashley and Boothroyd (1975). They determined from studies of Pleistocene glaciodeltaic deposits that sand-sized and coarser clasts constitute a significant portion of material deposited from density currents as distributaries migrate across the subaerial plain.

The silt sediment that overlies the sand facies would seem to represent deposition under the lower part of the lower flow regime (fig 3-2). The interesting aspect of this alternate coarse-fine succession is the lack of cross-laminated units incalated between the units A2 and C facies. These cross-laminated units indicate a gradual reduction in current velocity. The silt units present no visible internal structure. Deposition may have resulted from slow moving currents from a distal sediment source. With a sudden reduction in the supply of coarse-grained sediments and the distal position of the ice front, currents would transport and deposit silt during low flows. The coarse-textured silts could represent lateral accretion deposits laid down in quiet backwater areas of distributaries by late or early season currents. The possibility exists that currents may have continued throughout the winter depositing silt sediment. Gustavson (1975) observed that

meltwater discharge occurred year-round in proglacial Malaspina Lake, and that bottom-melting in winter produced reduced discharges in comparison to summer flows. Jopling and Walker (1968) also interpreted deposition occurring throughout the year in a Pleistocene kame delta. The lack of any clay layer found over the kame delta deposits was used to support their assumption. Clay laminae do not occur over the silt units in log 2 and only appear at unit 10 in log 4. Therefore, deposition may have continued by density underflows throughout the winter season. The following presents an interpretation of the depositional environment of these lower units.

Logs 2 and 4 occur close to present day tributary streams feeding into Okanagan Lake. There is the possibility that these lower alternating units may have been deposited in inter-distributary channels of tributary deltas which were prograding into the proglacial lakes on either side of the ice occupying the center of the valley. The coarse sediment would have been deposited by density currents in distributary channels during the melt season following Walker's (1967) grain segregation process (p.49), "...at relatively high flow regime a thick traction carpet with high grain concentration can be maintained and a structureless bed forms upon deposition in the proximal environment." Sharp tops and bases are also indicators of proximal deposits by Walker. The sudden change to silt-facies may be accounted for by the sudden reduction of stream flow and low sediment input from a distal source. Mountain streams follow similar discharge

characteristics. Faulting in the units may be interpreted as removal of ice contact support as the central glacier downwasted and the proglacial lakes increased in depth.

Further support for this interpretation stems from Nasmith (1957), Fulton (1965) and Flint (1935) who proposed that higher elevations would be ice-free first, and sediment would be transported to the valleys where the proglacial lakes would be developing. Recent research by Kvill (1977) and Archer (pers comm) also considers tributary deltas as prograding into the developing proglacial lakes early in the stratigraphic position of the sediments.

The second succession of facies is most evident in log 7 where flat-bedded sands and cross-laminated deposits exhibit a cyclic alternation. Flat-bedded sands (A2) are predominant in the lower stratigraphic positions. Units 1-5 inclusive of log 7 are composed of thick flat-bedded sands with horizontal bedding succeeded by a thin contorted layer of draped silty-clay. These layers are indicative of deposition from suspension in deeper water. Higher in the stratigraphic position the flat-bedded sands grade into type A (trough or tabular) cross-laminae with stoss-side erosion, with superimposed type B climbing ripple-drift with stoss-side preservation. Units 16, 17 and 18 form an excellent example of this sequence. In some units the flat-bedded sands underlie type B ripple drift (units 19, 20, 36, and 37). In other instances type A is succeeded by flat-bedded sands (units 9, 10 and 11). The lower units of material are coarser, medium sand, and there is an upward

fining trend where sand becomes finer.

The cyclicity of these units provide a more complex interpretation of the flow processes and depositional environment. The flat bedded sands showing poor sorting of the sediment supports the idea of an environment characterized by upper flow regime. The origin and depositional environment proposed earlier in this section for flat-bedded sands are again considered valid for the units in log 7. However, the difference for these channel fill deposits is the erosional contact between, and upward fining into, the cross-laminated units. Climbing ripple-drift are facies states considered by many researchers as originating from low velocity currents and occurring distally from the sediment source Jopling and Walker (1968), Gustavson (1975), Ashley (1975), Walker (1967) and Allen (1970).

Jopling and Walker (1968) proposed that with a continued reduction in current velocity in the lower part of the lower flow regime (fig. 3-2) type A cross-lamination with stoss-side erosion represents less sediment falling-out of suspension to bury the grains moving on the bed; whereas, type B with stoss-side preservation has a higher suspension/traction ratio. Jopling and Walker considered that these structures may have resulted from deposition by density underflows in a glacial lake environment. The high rate of deposition from suspension with bed-load movement resulted in type B, while bed-load movement with little suspended sediment deposition resulted in type A cross-lamination. Walker (1967)

believes that turbidity currents form cross-laminae structures in the following two ways: one, sediment re-worked at suitable flow regimes and two, formed during primary deposition. If re-worked,the cross-laminae sets would be thin and confined to proximal environments. However, primary deposition will result in thicker sets and ripples will climb and form ripple-drift cross-laminae (p. 49). Walker invoked a coarse to fine (plane to rippled bed) sequence through grain segregation by development of a traction carpet process. He states,

> ... A thick set of parallel laminae, graded from bottom to top, would develop at relatively high regimes (plane bed with grain movement, Simons et al, 1965), and ripple-drift cross laminae would develop as the result of fallout in a lower flow regime (rippled bed) (p. 49).

From the above discussion, the upward-fining cross laminated facies can be attributed to density underflows losing competence and depositing ever-increasing sediment from suspension distally on the deltaic plain. Gustavson, Ashley and Boothroyd (1975) indicate that ripple drift cross-lamination predominates in prodelta slope deposits. Gustavson (1975) also observed exposed ripple-drift in a glaciolacustrine prodelta slope. Although these observations have been made, Shaw (1975) offers a more complete explanation of sedimentary processes resulting in the succession from flat-bedded sands to cross-laminated sands. He suggests that as currents flow into standing lake water high sedimentation creates deposition on shoalwater distributary-mouth bars. These features exhibit rippled surfaces and cross-

lamination is predominant. The lack of dune structures indicate that deposition occurred in shallow depths. Shaw summarizes as follows,"... Therefore, it is plausible to suggest that the transition from flat-bedded sand to cross-laminated occurred as a result of reduced depth and velocity of an expanding flow over a distributary-mouth bar." (p. 327) Paleocurrent directions also support this interpretation. Directions are not consistent from each unit as would be expected from lateral accretion deposits. The slight fluctuation in paleocurrent directions is probably the result of migration of distributary-mouth bars. Gustavson, Ashley and Boothroyd (1975) propose that,

> ... As the position of the distributaries on the delta subaerial plain changes, as does the lobes (distributary mouth bars), resulting in the lakeward construction of the delta front by overlapping lobes of sediment. The continuous density flows that deposited the lobes also may shift laterally across the lobe. (p. 278).

Log 7 exhibits larger and more complex sequences of primary sedimentary structures that are also cyclical in nature. Log 2 from unit 8 to 23 illustrates flat-bedded sands, cross-lamination, alternating beds and parallel-lamination. However, except for units 20a, 21 and 22 there exists no consistent upward fining in the coarse sediments. The aforementioned hypothesis that the lower units may represent a small tributary delta is further supported by the lack of well-developed channel to distributary mouth bar deposits. Paleocurrent directions from units 15 and 22 indicate directions of flow from lateral tributaries rather than down valley.

The lower units of log 7 are interpreted as deposition in a prodelta environment. The flat-bedded sands are channel deposits with upward-fining cross-laminated sands being deposited in shoalwater distributary mouth bars.

5.3 Transition Environment

A transition zone (following fig. 5-1) is tentatively identified by the rhythmic alternation of facies A, A_2, B, C, and D. In log 7 these associations occur from unit 51-58 inclusive; log 2, units 23-26 and units 1-8 inclusive in log 5. The sequence of facies overlie the coarse-grained deposits in log 2 and 7 and underlie the fine-grained parallel-laminated silt and clay couplets.

The coarse members of these sequences are represented by facies A_2 and A, with finer members being facies B, C, and D. Loading and convoluted structures are common in these units: 35, 52, 55 and 56 (log 7) and 24 (log 2).

Fig. 5-2 illustrates cyclic deposits found in unit 58, log 7. Generally, flat-bedded sands grade into ripple-drift type A which becomes contorted followed by A_2 facies and parallel laminated silt (C) facies.

Coleman and Gagliano (1965) describe a sequence of structures where convolute laminations comprise certain zones (fig. 5-2). Convoluted sands and flaser structures are considered by some researchers to be the direct result of deposition from turbidity currents (Kuenen, 1952; Sanders, 1965) with deformation resulting from additions of fallout from turbulent suspension. They interpret deposition

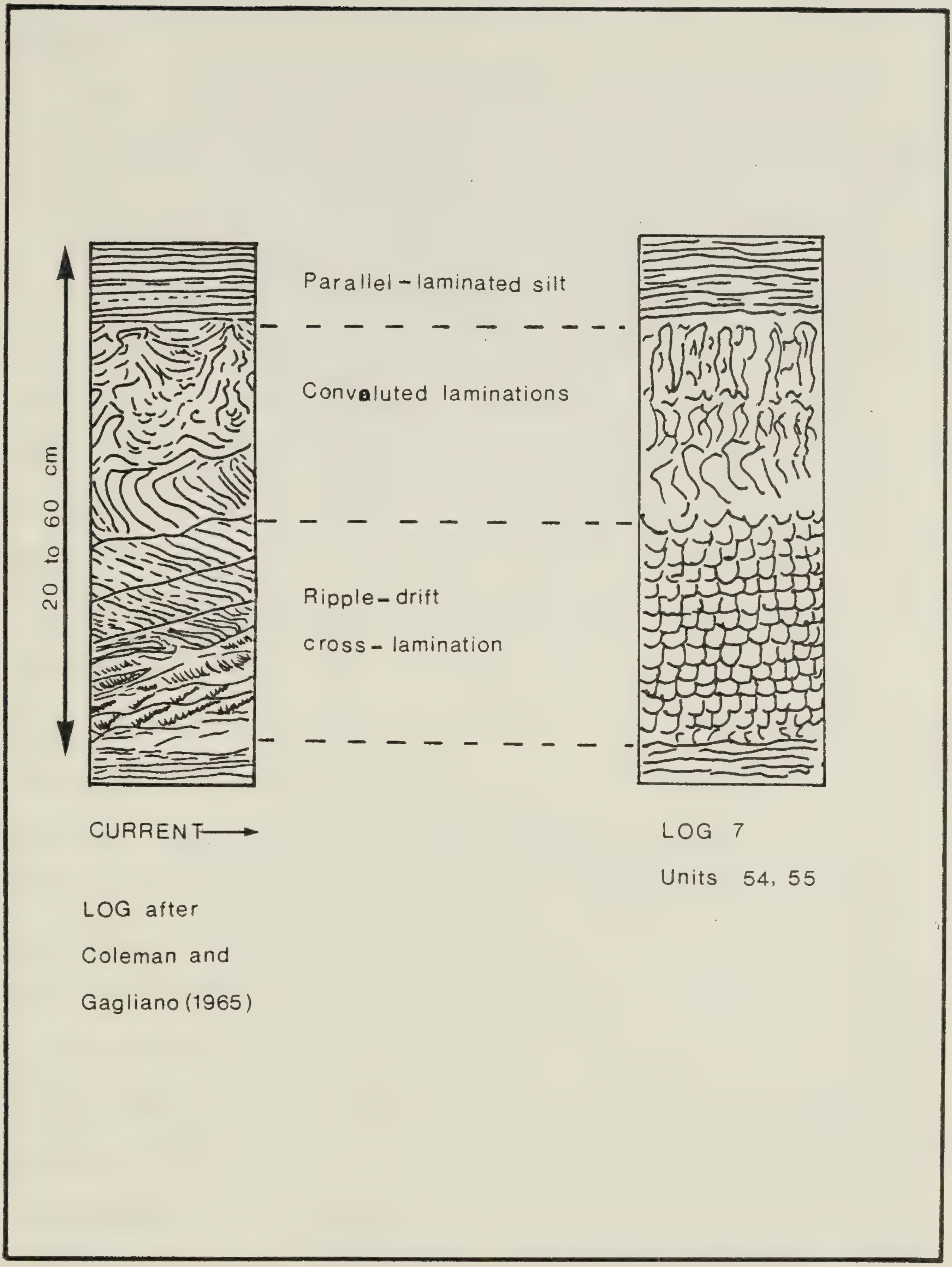


Figure 5 - 2 Comparison between convolute lamination sequences found in fluvial and lacusterine environments

through the sequence by increasing and decreasing current velocity.

The authors state (p. 139)

> ... Shear stress acting on the bottom is increased by a sudden rise in turbulence. If this occurs, a mechanism is provided for the production of the anticlinal and synclinal folds or convolute laminations. A sudden rise in turbulence may mark the abrupt transition between the lower and upper flow regimes. If this is the case, the parallel laminations capping the sequence could be attributed to deposition during the upper flow regime.

Conversely, a set of ripple laminations would imply a reduction in current velocity. Coleman and Gagliano observed these sequences in subaqueous levee and point bar deposits where velocity pulsations occur during flood stage.

A similar sedimentation process and depositional environment is proposed for the units found in log 7 (figs. 5-3, 5-4). The stratigraphic logs where these associations occur indicate the rapid alternation of not only bedform types but texture. The flat-bedded sands deposited by larger underflows could be subjected to heavy suspended sedimentation resulting in the ripple-drift grading into convolutions. The flat-bedded sands indicate high-flow regime (fig. 3-3) to low-flow regime for the ripple drift. The convolutions would occur with friction on the bed and heavy suspended sediment settling on to the topset. The overlying parallel-laminations of silt would then indicate an increase in velocity. Alternatively these parallel-laminations could indicate another underflow event that might not be large enough to carry coarse sand deposits, and the current deposited silt at a higher flow regime.

Fig. 5-3. Convoluted silt is succeeded by parallel-laminated silt. This sequence is found in unit 58, log 7. Scale of the unit is 30 cm.

Fig. 5-4. Flame structure. Found commonly in sands overlain by silts in the transition zone of log 7 and log 4. This photograph was taken at unit 52, log 7. Scale of feature is 5 cm.

Shaw (1975) recognized a rhythmic alternation within certain stratigraphic sections. Interpretation revealed that alternating beds and finer members resemble deposits associated with levée and interdistributary bay surfaces by vertical accretion from overbank flows. Analysis of the succession indicates that pulsating currents provide accumulations of coarser sediment through channel wandering and finer members are overbank levée and interdistributary bay deposits.

5.4 Varved Sediments

The largest proportion of the sediments in all the sections is composed of the silt and clay couplets, facies C and D (section 4-2). The lower silt units in the logs are coarse in texture, and exhibit flaser ripple formsets (units 8, and 10 in log 6; units 5, log 3; and unit 18, log 2), and type B climbing ripple drift (log 3, units 5, 9 and 11; log 5, units 6, 10; log 2, unit 32). These structures usually occur one-third or half-way up the unit. Fulton (1965) observed this same phenomenon in the lower silt units of South Thompson Valley. The occurrence of cross-lamination could be interpreted as the infusion of fine-grained sand and coarse silts deposited by underflows in response to periods of maximum inflow. The finer sediments in the tail of the current could have been worked into cross-lamination by the 'traction-carpet' mechanism in distal environments proposed by Walker (1967). Also, palaeocurrent directions in these ripple drift units are orientated down valley. The later or

ongoing currents would contribute the fall-out of suspended sediment aiding in the preservation of these ripples. Gilbert (1973) observed isolated underflow events during continuous interflow and overflows. However, he failed to identify structures, in core samples, relating to these isolated underflows. It could be inferred that although underflows are common in some active modern glacial lakes, the Pleistocene ice-marginal and proglacial lakes would have produced substantially stronger currents able to form cross-lamination prior to the cessation of the current. Fulton (1965), identified sub-units of small scale cross-lamination in lower silt laminae. Visher (1965) concludes that deposition of structures (in lacustrine sediments) occurred under conditions of pulsating currents surging below the relatively still waters of a glacial lake. However, with a vertical rise in the sections the structures no longer occur, and the laminae are composed of structureless units. But, as the grain size analysis indicates, the silt in the unit is not graded, but shows marked intrusions of coarser grained deposits. Interpretation suggests that continuous interflow and overflow would be depositing sediment from suspension, creating graded units with single underflows occurring in response to greater discharge. Sanders (1965) supports this interpretation noting that structureless fine-grained deposits are also formed by long-continued deposition from turbulent suspensions, as for example, steady turbidity currents of low density entering a lake. Therefore, the environment is

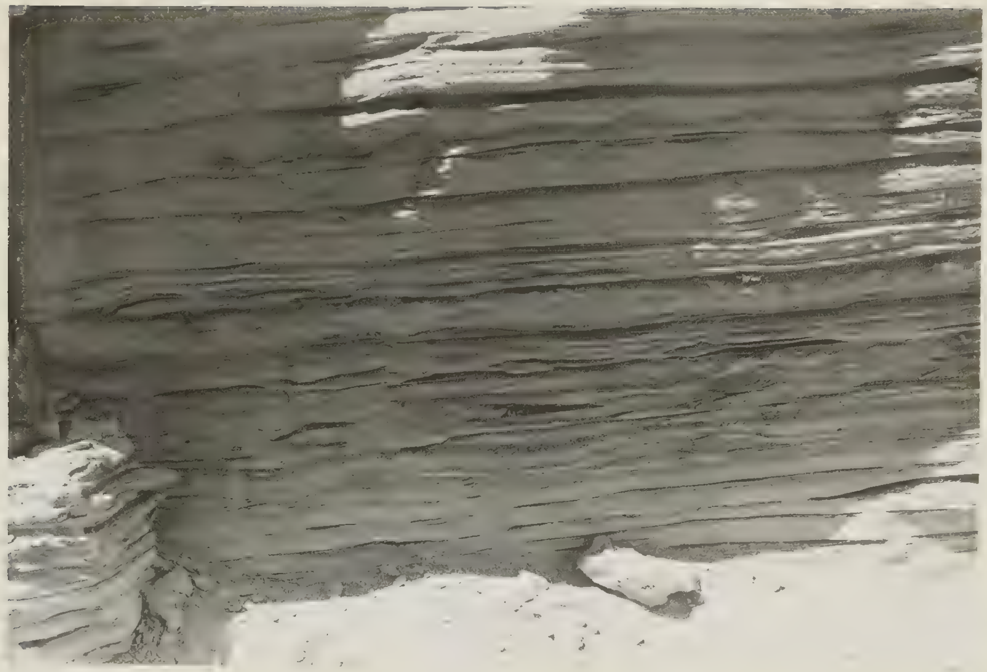


Fig. 5-5. Ripple formsets grading upwards into wavy lenticular stratification of alternating silt and fine sand. These units occur in the transition zone, unit 56, log 7. Scale of these associations is 45 cm.

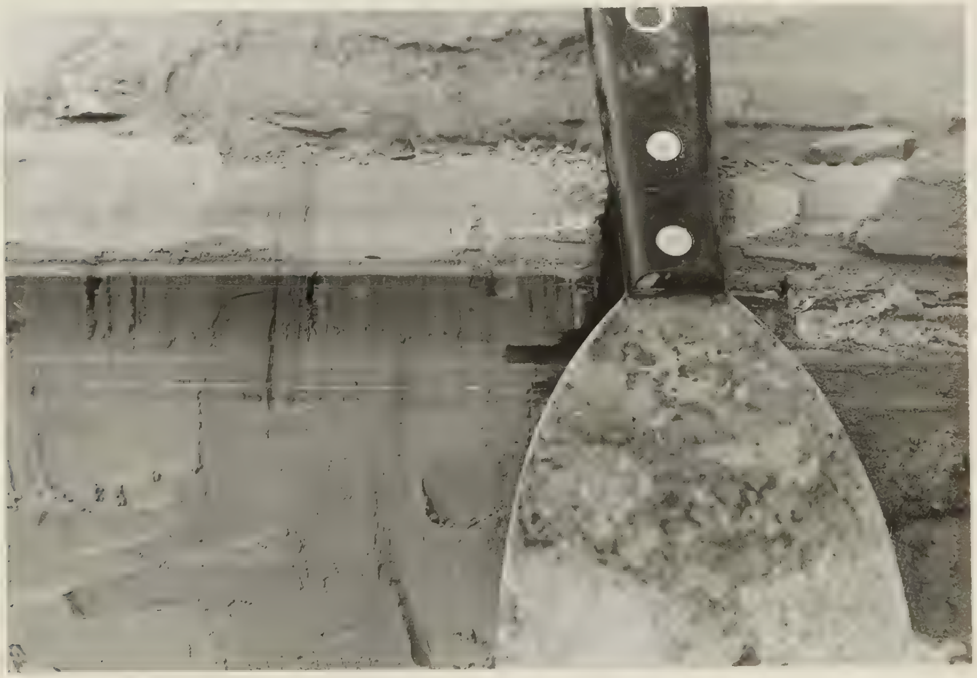


Fig. 5-6. Parallel laminations of alternating silt and clay grading upwards into the clay winter layer. This photograph illustrates the sharp upper contact (silt over clay) and gradational nature of both lamina, unit 40, log 1. Scale of the winter layer is 5 cm.

changing to a more distal state where sedimentation is increasingly from suspension. The middle and upper units of the sections reflect the processes found in active glacial lakes, although the size of the laminae found here are still very much larger.

Silt laminae in the upper sections exhibit laminations, especially at the top of the unit prior to the winter layer (fig. 5-6). These laminations could be indicative of diurnal or increased sediment influx (Chapter II) and would be associated with underflow events responding to possible late autumn storm events. Fig. 5-7 shows a common feature found in the upper clay units in logs 1 and 6. These sand stringers are found in the winter layer and are composed of coarse sand. Shaw (pers comm) believes these structures originated from turbidity currents active during winter. Shaw has found current structures in these coarse sediments, indicative of deposition by currents. Intermittent periods of warming or slump generated currents probably created isolated current activity.

The varved sediments indicate the depositon of the silt laminae in the lower units to underflow events, especially where bedforms occur; however, deposition from suspension seems to be the dominant process in the higher units. With increasing vertical height above the base of the sections the silt-clay couplets become thinner. These resemble more closely those varves laid down by processes active in modern glacial lakes.

Fig. 5-7. A sand stringer commonly found in the winter layer of the upper units of the Summerland and south Summerland sections. These features could have originated from underflow events. Scale of the stringer is 0.5 cm.

CHAPTER VI

SUMMARY, CONCLUSIONS,

and SUGGESTIONS for FURTHER STUDIES

6.1 Summary

The present study has been an attempt to determine the sedimentary processes responsible for the extensive terraces of fine-grained lacustrine deposits found in the Okanagan Valley. Moreover, by elucidating the depositional processes the environmental conditions in which they operated may be reconstructed.

Specific emphases in the study have been the determination of the dominant mechanisms of varve deposition and an attempt to correlate varved units from seven measured sections in the valley.

The physical setting has been fully described in Chapter I. In summary, the Okanagan Valley is a narrow north-south trending valley that was subject to the development of a proglacial lake - Lake Penticton - during deglaciation. The lake was fed by lateral streams carrying high volumes of sediment from ice-free upland areas. Upon the draining of the lake, lacustrine sediments were found underlying terraces in exposed cliffs bordering Okanagan Lake. The post-glacial climatic conditions have been sufficiently arid to preserve the glacial lake sediments offering good exposures for measurement.

Literature dealing with Pleistocene and modern lacustrine sedimentary studies have been reviewed and used to help analyze the depositional environment of glacial Lake Penticton. In addition, literature dealing with turbidity current mechanisms, and flow regime in the formation of varved sediments was extensively drawn upon to help in interpretation of sedimentary processes.

The major field work of the research was conducted on seven sections, three on the east side of Okanagan Lake and four on the west side. Sedimentary processes were elucidated by the measurement and recording of the geometry (shape and size of the stratigraphic units), texture, primary sedimentary structures, deformation structures and paleocurrent directions. In the laboratory grain size analysis was conducted on silt samples taken at 10 cm intervals from a thick silt unit in all seven sections. Five facies states were assigned to describe the sedimentary units and aid in analysis. An attempt was made by a linear correlation program to correlate the varves in all seven sections.

Interpretation of the results of the field research indicated that the deposits found in the lower parts of certain sections were coarse-grained sand deposits. The facies states show vertical cyclic alternation of flat-bedded sands overlain by cross-laminated sands. Stuctureless sands commonly underlie type A cross-laminated with stoss-side erosion with superimposed type B climbing ripple drift with stross-side preservation. Flow interpretation suggests rapid bedload deposition in the lower part of the upper flow

regime for the flat-bedded sands, and the lower flow regime for the cross-laminated units. The flat-bedded sands are interpreted as channel fill deposits laid down in deltaic distributaries. The cross-laminated units are considered to be distributary mouth bar deposits laid down by currents in the prodelta environment. Paleocurrent directions support this analysis. The conclusion is supportive of similar findings in glaciodeltaic sediments by Shaw (1975), Ashley (1975), Ashley,Gustavson, and Boothroyd(1975) and Gustavson (1972).

Further interpretation of the field research indicates that vertically in the stratigraphic units of log 7, a transition zone exists where laminated silts alternate with convolute and flaser sand structures, ripple formsets,climbing ripple drift and flat-bedded sands. The flow regime indicates an alternating shift from upper to lower flow regime where subsequent meltwater flows create silts to become convoluted. Environmental interpretation suggests deposition associated with subaqueous levées and interdistributary bay surfaces. This conclusion is supported by findings in prodelta environments of Colemen and Gagliano (1965), Ashley, Gustavson and Boothroyd (1975), and Shaw (1975).

Parallel-laminated couplets of silt and clay (varved) comprise the uppermost portion of each section. Field analysis revealed that the lower silt units are massive (up to 200 cm) and thin vertically toward the top of the sections.

Grain size analysis indicates that a silt unit is not graded as a turbidite i.e., coarse to fine. Moreover, the silt alternates between coarser and finer fractions with sorting being generally poor. However, interpretation suggests that silt laminae in glacial Lake Penticton were deposited by continuous currents over the lake floor, carrying finer material, with occasional influx of coarser better-sorted material as a result of more powerful underflow events.

The attempt to correlate varved units in each section was unsuccessful. The computer program correlated units on the basis of thickness and the thicker beds lower in the units dominated the correlation.

6.2 Conclusions

The study of the lacustrine sediments indicates rapid sedimentation into, and development of, glacial Lake Penticton. Figure 6-1 presents a three stage model illustrating the depositional environment based on the study's findings.

The lower coarser-grained sediments indicate deposition in glaciolucustrine deltas. Analysis and interpretation of sedimentary associations, flow regime for facies states, paleocurrent directions and disturbance suggest that tributary streams built up prograding deltas against a downwasting stagnating tongue of ice occupying the valley bottom. The sediments indicate high energy proximal depositon with faulting the result of removal of ice support. This first stage of the development of the sediments is illustrated in fig. 6-1.

In fig. 6-1, stage II, the lake developed in size from the downwasting glacier, isostatic uplift, and outlet adjustments at Okanagan Falls. The sediment entering the lake was from a more distal source. The result was the development of the-finer-grained alternating facies laid down in the prodelta environment on top of the coarser distributary deposits.

In Stage III the lake reached full development, and finer-grained deposits were deposited from a more distal sediment source. Silts were laid down in summer by turbidity currents and upon freezing in winter the clays settled out of suspension forming the "classic" varve couplet.

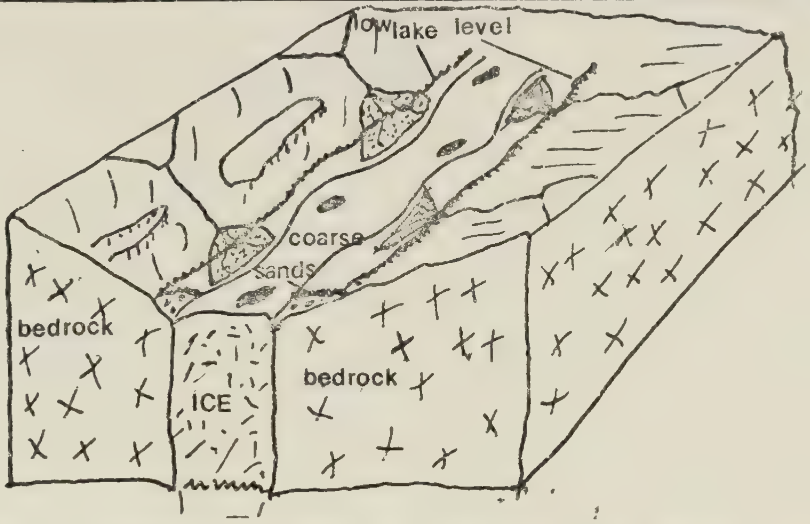
De Geer (1912); Antevs (1925) and Hughes (1965) used the number and spatial arrangement of varves to indicate age and retreat of ice during development of Pleistocene glacial lakes. Based on the number of fine-grained varved units occuring in the upper parts of each section, Lake Penticton was only at its deepest for a short period of time. The maximum number varves occuring in the upper parts of the terraces are of the order of 84 (log 7). However, allowance must be made for erosion, error in sampling and an insufficient knowledge of the sublittoral sediments in Okanagan Lake. Therefore, a longer period of existence for glacial Lake Penticton may be correct if more knowledge was obtained on the sediments below the terraces. This conclusion is supported by Fulton (1965) who expressed that sedimentation in glacial Lake Thompson was rapid and the life of the lake was

short. In connection with this final stage of development, attempts were made to find any strandlines of glacial Lake Penticton. However, no evidence of these were discovered during the field research. Kvill (1976) utilized remote sensing techniques in an attempt to discover former levels of glacial Lake Penticton. Unfortunately, agriculture and cultural activity has masked the surface texture patterns and obscured any evidence that may exist.

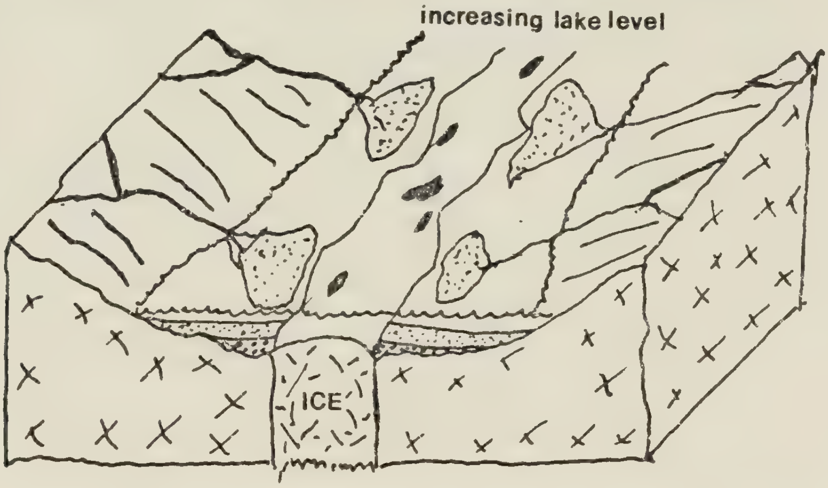
6.3 Suggestions for Further Study

In the course of the present study particular subjects requiring further research in the study area have been identified; namely, correlation of the varved units between sections. There is a fundamental need for more exposures to be assessed so that a more detailed history of the depositional processes can be recorded, especially in the Westbank, Kelowna and Vernon regions.

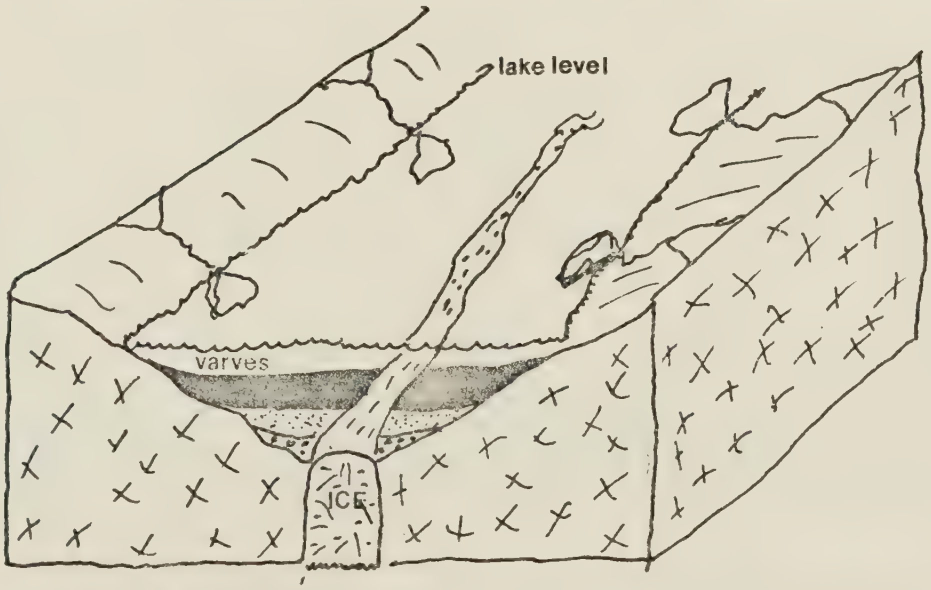
It would also be useful to follow the seismic survey work on Okanagan Lake with bottom core samples. Fulton (1970) found thick (120 m) unit of silt from a borehole near Armstrong. The information from these cores may define the depth and texture of the sediments during early deglaciation of the Okanagan Valley.



STAGE 1 Development of glaciolacustrine deltas into developing Lake Penticton.



STAGE 2 Deposition of alternate coarse and fine sands and silts in a prodelta environment.



STAGE 3 Deposition of varved sediments as the sediment source becomes more distal and Lake Penticton develops

Figure 6–1 A three stage model of sedimentary processes active in glacial Lake Penticton

APPENDIX I

```
MTS   FORTRAN IV G COMPILER (O/S REL 21.6)          MAIN              11-05-74      14:03.13      PAGE 0001
               C      CALCULATES PEARSON COEOFICIENTS FOR CORRELATING VARVE SERIRS, OVERLAP +,-5
  0001                DIMENSION A(7,83),X1(83),Y1(83),LR(7)
               C      NS = TOTAL NUMBER OF SERIES
               C      LR = LENGTH OF EACH SERIES
  0002                MR=83
  0003                NS=7
  0004                READ(5,1000)(LR(I),I=1,NS)
  0005         1000   FORMAT(12I2)
  0006                DO 10 J=1,MR
  0007                READ(5,1001)(A(I,J),I=1,NS)
  0008         1001   FORMAT(12F5.1)
  0009         10     CONTINUE
  0010                NS1=NS-1
  0011                DO 1 II=1,NS1
  0012                K3=II+1
  0013                DO 2  JJ=K3,NS
  0014                WRITE(6,40)II,JJ
  0015         40     FORMAT('1',10X,'SERIES',2I5//)
  0016                DO 8 J=1,MR
  0017                X1(J)=A(II,J)
  0018         8      Y1(J)=A(JJ,J)
               C      CORA STARTING WITH X1 AND Y1
  0019                K1=LR(II)
  0020                K2=LR(JJ)
  0021                ISY=1
  0022                ISX=1
  0023                IEX=K1
  0024                DO 117 IEY=IEX,K2
  0025                CALL CORA(ISX,IEX,ISY,IEY,X1,Y1)
  0026                ISY=ISY+1
  0027         117    CONTINUE
               C      SHIFT X DOWN
  0028                ISX=1
  0029                IEX=K1-1
  0030                IEY=LR(JJ)
  0031                K4=IEY-IEX+1
  0032                LM=IEY-4
  0033                DO 84 ISY=K4,LM
  0034                CALL CORA(ISX,IEX,ISY,IEY,X1,Y1)
  0035                IEX=IEX-1
  0036         84     CONTINUE
               C      SHIFT Y UP
  0037                IEX=LR(II)
  0038                ISX=IEX-4
  0039                ISY=1
  0040                K5=IEX-1
  0041                DO 74 IEY=5,K5
  0042                CALL CORA(ISX,IEX,ISY,IEY,X1,Y1)
  0043                ISX=ISX-1
  0044         74     CONTINUE
  0045         2      CONTINUE
  0046         1      CONTINUE
  0047                STOP
  0048                DEBUG SUBCHK
  0049                END
```

```
MTS   FORTRAN IV G COMPILER (O/S REL 21.6)          CORA              11-05-74      14:03.27      PAGE 0001

 0001                  SUBROUTINE CORA(ISX,IEX,ISY,IEY,X1,Y1)
 0002                  DIMENSION X1(83),Y1(83)
 0003                  N=IEX+1-ISX
 0004                  SXSQ=0.0
 0005                  SYSQ=0.0
 0006                  SX1=0.0
 0007                  SY1=0.0
 0008                  SX1Y=0.0
                 C     SUM X1, SXSQ
 0009                  DO 3 I=ISX,IEX
 0010                  SX1=SX1+X1(I)
 0011                  SXSQ=SXSQ+(X1(I)**2)
 0012            3     CONTINUE
                 C     SUM Y1,SYSQ
 0013                  DO 4 K=ISY,IEY
 0014                  SY1=SY1+Y1(K)
 0015                  SYSQ=SYSQ+(Y1(K)**2)
 0016            4     CONTINUE
                 C     SUM X1 MULT BY Y1
 0017                  L=ISY
 0018                  DO 5 M=ISX,IEX
 0019                  SX1Y=SX1Y+(X1(M)*Y1(L))
 0020                  L=L+1
 0021            5     CONTINUE
                 C     CALCULATE R
 0022                  R=((N*SX1Y)-((SX1)*(SY1)))/((((N*SXSQ)-(SX1**2))*((N*SYSQ)-(SY1**2
                      1)))**.5)
                 C     CALCULATE F STATISTIC
 0023                  F=((R*R)/(1-(R*R)))*(N-2)
 0024                  WRITE(6,50)R,ISX,IEX,ISY,IEY,F
 0025            50    FORMAT(1X,'R:',F8.4,10X,'ISX=',I2,10X,'IEX=',I2,10X,'ISY=',I2,10X,
                      1'IEY=',I2,10X,'F:',F8.4,/)
 0026                  RETURN
 0027                  DEBUG SUBCHK
 0028                  END
```

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